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RESEARCH ON THE POLARIZATION OF LIGHT FROM PLANETS AND FROM SOME TERRESTRIAL SUBSTANCES

by B. Lyot

From *Annales de l'Observatoire de Paris, Section de Meudon*
Vol. VIII, No. 1, 1929

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By B. Lyot

Translation of "Recherches sur la polarisation de la lumière des planetes et de quelques substances terrestres

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Section de Meudon
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Book I

RESEARCH ON THE POLARIZATION OF LIGHT FROM PLANETS AND FROM SOME TERRESTRIAL SUBSTANCES

by B. LYOT
Assistant Astronomer at the Observatory

1929

To Monsieur Henri Deslandres, Membre de l'Institut,
Director, Paris Observatory

and

Monsieur Charles Fabry, Membre de l'Institut,
Director General, Institut d'Optique
Professor, Faculty of Sciences, University of Paris
and École Polytechnique

As a token of deep and respectful gratitude

Translator's Note:

The author uses the term "simple scattering" to indicate "simple reflection" as given by Snell's Law. The original term has been retained throughout.

FOREWORD

This is the first of three related theses that complement each other and form a summary of the photometry and polarimetry of the moon.

The other two theses in this series are:

STUDY OF THE PLANETS BY MEANS OF THE POLARIZATION OF THEIR LIGHT, by Audoin Dollfus, 1955 (NASA TT F-188)

PHOTOMETRIC PROPERTIES OF LUNAR CRATER FLOORS, by J. Van Diggelen, (NASA TT F-209)

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RESEARCH ON THE POLARIZATION OF LIGHT FROM PLANETS AND FROM SOME TERRESTRIAL SUBSTANCES

PART ONE—ASTRONOMICAL RESEARCH

Introduction

To date planets have been studied by two methods:

1. By observation of the details on their surfaces, made directly through a lens or by the intermediary of a photographic plate.

2. By analysis of the radiations they emit, including the analysis of intensities, wavelengths, or state of polarization.

The observation of planetary details commenced with the invention of the telescope and this slowly furnished results which have only recently been broadly confirmed by photography. Spectral analysis, photometry and the study of polarization were applied to planets only later. These methods soon yielded interesting data concerning the rotation movement of the planets, and more recently, indications concerning their temperatures and their atmospheres. The study of polarization seemed full of promise during Arago's time, but since then, has not given any positive result regarding the planets.

This is seemingly a very surprising fact, since light, as scattered by all the various objects which surround us, is highly polarized. This is the reason why I have started research on this question which is the subject of the present work.

This work is divided into three parts:

Part One is related to the study of planets. This part is made up of three chapters:

1. Chapter I sums up observations made to date.

2. Chapter II describes the instruments and the experimental methods.

3. Chapter III presents the obtained results.

Part Two relates to light scattered by various terrestrial substances, and is presented with the same outline as Part One.

In Part Three I try to explain the results obtained from the planets by comparing them with those obtained from Earth substances, in order to show later the consequences entailed by these results and, finally, to draw some conclusions from the whole of this study.

The astronomical observations which will be mentioned were made, in great part, at the Meudon Observatory, thanks to the kindness of Mr. Deslandres who let me use the large telescope. I would like to express my sincere gratitude to him.

CHAPTER I. HISTORICAL BACKGROUND

Polarization of the Moon

The first work on the polarization of celestial bodies dates back more than a century. Observations of the Moon were first attempted because of its large apparent diameter. In 1811 Arago made eight observations on this satellite with his polariscope, which was made of a birefringent prism preceded by a flat plate of quartz. He found a polarization stronger on the seas than on the continents, with a maximum during the first quarter and an undetectable level three or four days before opposition (1). He explained the changes in polarization as due to the age of the Moon and to the hues on the ground of this planet, and assumed that the planet is surrounded by an atmosphere similar to ours and "light reflecting." These observations were confirmed in 1859, and later refined and completed by Secchi in 1860. He made the following remarks (2): The plane of polarization and the plane of reflection are the same, and the ratio of polarized light is almost independent of the different surface inclinations. "There is only a small difference between the illuminated edge and the area which is adjacent to the edge of the shadow."

Secchi rejected the theory of a lunar atmosphere and attributed the observed polarizations to the lunar ground. This ground has a mirror surface "on which it is always possible to find a suitably inclined plane to give a proportion of polarized light along the general angle of reflection." The works which followed were directed towards finding the nature of the rocks composing the lunar ground.

In 1877, Lord Rosse studied the changes of polarization on different parts of the lunar surface, with a polarimeter almost identical to that of Arago. The purpose of that study was to find the angle of maximum polarization and to compare it with that of vitreous volcanic media. According to his published data (3), the ratio of polarized light from Mare Crisium goes through a maximum when the Moon is at an angle of 88° with respect to the Sun; then it is equal to 12%. After the first quarter the ratio first decreases very rapidly, then slowly, then becomes undetectable around the full Moon. He drew no conclusions from his results because he did not possess data on terrestrial rocks.

Landerer (4), in 1889, tried to solve the same problems with a Cornu photopolarimeter by studying the average polarization of the central regions of the crescent, instead of localized points. He obtained values smaller for the first quarter than for the last, which he explained by the fact that the area of illumination of the seas is less during the first quarter. His measurements

(1) ARAGO, Oeuvres, Vol. 10, p. 564, Astronomie populaire, Vol. 3, p. 463.
(2) SECCHI, Monthly notices, Vol. 19, 1859, p. 290, Astronomische Nachrichten, Vol. 52, 1860, p. 93.
(3) LORD ROSSE, Proceedings of Royal Dublin Society, Vol. 1, 1878, p. 19, this article is reproduced in many publications.
(4) LANDERER, Comptes rendus, Vol. 109, 1889, p. 360.

gave a maximum angle of polarization of 33°17' for the lunar seas, corresponding to an angular distance between the Sun and the Moon of 113°26'; these measurements were very different from the ones found by Lord Rosse. The ratio of maximum polarized light was 20.7% towards the first quarter and 32.9% towards the last (1).

Landerer also studied ice and various polished volcanic rocks (2) and found for vitrophyre, an angle of polarization equal to that of the Moon. The surface of the Moon thus seemed to contain this rock in great abundance and did not appear to be covered with ice. These conclusions were not considered final because the polarization measurements were not sufficiently accurate to enable him to determine the angles of polarization for the Moon in a satisfactory way.

Salet (3) showed in 1922, that the angle of maximum polarization of a rock varies with the degree of surface polish. For this reason he thought that it was impossible to deduce the angle of polarization for the lunar ground from observations such as the ones performed by Lord Rosse. Landerer's measurements, on the other hand, have the disadvantage of having been made on different regions which can differently polarize light.

Finally, Barabascheff (4), in a work performed subsequent to my research, recently measured the ratio of polarized light from the seas and from the continents with a Cornu photopolarimeter in order to compare the polarization with terrestrial rocks having approximately the same albedo. He found for the seas a broad maximum of 47.2%, corresponding to a polarization angle of from 33°57' to 37°11'. On the continents the maximum was 17%. Landerer's conclusions appeared doubtful to Barabascheff because of the broad shape of the maximum. From a comparison of the lunar curve with the curves which he found for numerous terrestrial rocks, he estimated that the Moon must be covered with sandy material.

These works seem to contradict each other and to give very different results, depending on the method and the instruments used in the measurement. The Cornu polarimeter gives much higher values than the Arago polarimeter, according to the figures given by Landerer and especially by Barabascheff, which are four times higher than those of Lord Rosse for the seas.

A few perplexing results were obtained during Moon eclipses. During the eclipse of 31 May 1844, Arago (5) observed "definite traces of polarization" in the "reddish light distributed on the lunar disk at the conjunction time." The existence of this polarization has been confirmed by all his collaborators. Zantedeschi (6) made a similar observation during the eclipse of 24 November 1844.

---

(1) These high figures do not agree with the observations made by Lord Rosse. The measurements made by the latter led him to predict that, for a region covering both continents and seas, the ratio of polarized light should not exceed 12%.

(2) LANDERER: On the Polarization of Igneous Rocks, Comptes rendus, Vol. 11, 1890, p. 210.

(3) SALET, L'Astronomie, 1922, p. 408.

(4) BARABASCHEFF, Astronomische Nachrichten, Vol. 229, 1927, p. 7.

(5) ARAGO, Comptes rendus, Vol. 18, 1844, p. 1119.

(6) ZANTEDESCHI, Comptes rendus, Vol. 19, 1844, p. 1318.

During the eclipse of 27 February 1877, Freeman (1) observed the Moon through a doubly refracting prism mounted on the eyepiece of a telescope of 0.087 m aperture. By rotating the prism, he observed complementary intensity variations of the two images of the Moon with a period of 180°, which was a definite proof of the existence of polarization. He added however, that "It was impossible to determine the character of this polarization." None of these authors indicate the direction of the plane of polarization. During the eclipse of 31 May 1920, Salet (2) observed the Moon through a narrow fringe Savart polariscope. He did not find any trace of polarization in the different parts of the shadow, and found it difficult to believe the results of the first observations.

Polarization of the Planets

The planets were also subjected to research, but no positive result has been obtained for them. Secchi (3) wrote in 1859: "The full Moon is not polarized at all, and Jupiter, Saturn and Mars are no more polarized than our clouds; in other words, the polarization is undetectable."

Lord Rosse (4), however, following a series of measurements made on Venus from 12 March to 6 April 1872 with a polarimeter similar to that of Arago, found a weak polarization for that planet: "No regular variation has been observed for the polarization, despite considerable phase changes during this time interval." The mean value of this polarization (which is defined as the ratio of the components of polarization parallel and perpendicular to the plane going through the Sun) was 0.925, which corresponds to a ratio of polarized light of 3.9%. The direction of the plane was not clearly mentioned, but the notes which were made indicate that it was the same as that for the Moon, namely; parallel to the direction of the Sun.

Landerer (5), however, made a series of almost daily observations on Venus, from 29 April 1892 (date of the highest evening elongation) to 8 June 1892, "to measure its angle of polarization in order to deduce the petrographic nature of the ground of Venus." He used a Cornu photopolarimeter adapted to a 0.135 meter telescope. "From this research, the conclusion is that light coming from the Venus crescent is not polarized." The author concludes further that the surface of this planet is made up of a thick layer of clouds, and is in agreement with the ideas of Trouvelot, which were based on visual observations.

In 1894, W. H. Pickering (6) announced that he had observed on June 4 of that year, with an Arago type polarimeter, a dark zone along the polar cap of Mars which showed some polarization. At the next appearance the same region did not show any polarization. He concluded that this zone is in the state of a liquid surface which reflects light scattered by the clouds of the polar regions.

---

(1) FREEMAN, Nature, Vol. 15, 1877, p. 398.
(2) SALET, L'Astronomie, June 1920, p. 256.
(3) SECCHI, Monthly notices, Vol. 19, p. 290.
(4) LORD ROSSE, Proceedings of the Royal Dublin Society, Vol. 1, 1878, p. 19.
(5) LANDERER, Comptes rendus, Vol. 114, 1892, p. 1524.
(6) PICKERING, Astronomy and Astrophysics, The Sideral Messenger, Vol. 13, 1894, p. 554.

Finally, Salet (1), in 1906, studied the polarization of Mercury with the 600X equatorial of the East tower of the Paris Observatory. He first used an Arago type polariscope, which has the advantage of being insensitive to atmospheric polarization, and then used a very narrow fringe Savart polariscope with at least three fringes on the planet. In the second case he carefully made the observations through red glass in order to reduce atmospheric polarization when Mercury was sufficiently far from the horizon, so that better images could be obtained.

None of these methods showed any polarization on Mercury. The author believes, however, that the planet must have a constitution similar to that of the Moon, as demonstrated by its weak albedo. The preceding observations, repeated for the Moon with the unaided eye, gave him a negative result, which proves that the polarization on Mercury may have escaped him because of the smallness of the disk of this planet.

Present Status of the Question

The work summed up in this chapter has yielded very few positive results. For the Moon we know approximately how the polarization varies around the first quarter, but it is impossible to ascertain its value, even in a very rough way. It therefore seems premature to use the data to establish the nature of the rocks which form the lunar ground.

Eclipse observations would indicate that the polarization is very high, and is as indicated by polarimeters of low sensitivity (used on very dim sources such as the eclipsed Moon). These observations are unfortunately too vague to provide a valid explanation.

As far as planets are concerned, the polarization found by Lord Rosse was not confirmed by Landerer. The observation made by Pickering on Mars has not been verified. Lastly, the measurements on Mercury, Jupiter and Saturn have only given negative results.

The polarimeters used for these observations can, under good conditions, detect as little as 1% of polarized light. We are tempted to conclude that the polarization of planets is less than 1%, but such a conclusion, far from being certain, is hardly probable for the case of Mercury, as shown by Salet. Under these conditions I have decided to completely repeat the work reviewed here with more sensitive equipment.

The object of the present thesis is essentially to present and, as much as possible to explain, the results obtained on the Moon and on the first five planets.

---

(1) SALET, Comptes rendus, Vol. 143, 1906, p. 1125. Thesis, 1910, p. 50.

CHAPTER II. INSTRUMENTS AND EXPERIMENTAL METHODS

Properties of Polarized Light

First let us review the quantities that we measure in order to define a partially polarized light. A beam of partially polarized light can be considered as resulting from a mixture of a beam of natural light with a beam of totally polarized light whose vibrations are either linear or elliptical. The ratio of polarized light is equal to the ratio of flux of totally polarized light to the total flux of light. The plane of polarization, defined by the angle it makes with a known direction, is a plane passing through the light ray direction and normal either to the light vibrations if they are linear, or to the major axis of the vibrations if they are elliptical. In this second case, it is also necessary to define the ellipticity, or ratio of the major to the minor axes, and the direction of rotation. According to universal conventions, the ellipse will be termed left or right handed depending on whether the observer who receives the light sees the light vector turn in the counterclockwise or clockwise directions, respectively.

Research on a Suitable Polarimeter

The analysis of light from planets requires the use of a polarimeter especially adapted to the study of light containing a very small amount of polarized light. Three devices permit this kind of study: the Arago polariscope, the Cornu photopolarimeter, and the Savart polariscope. We shall examine the advantages and disadvantages which they present with respect to the goal we have in mind.

The Arago Polariscope

The polariscope designed by Arago is made up of a doubly refracting prism preceded by a quartz plate cut parallel to the optic axis and sufficiently thin to show very bright colors under polarized light. It can be easily mounted in front of the telescope eyepiece and yields under these conditions two images of the planets which appear tinted with complementary colors if the light of the planet is polarized. The polariscope lends itself easily to diurnal observations because the sky light provides a white background in the central portion of the field, regardless of the polarization of the sky. When the polarization of a planet is measured by compensating it, as Arago used to do it with a pile of plates for example, the sky light does not introduce any systematic error; it simply reduces precision of the measurement.

The smallest ratio of polarized light which can be detected with this type of instrument is approximately 1.2% (figure given by Arago). With smaller polarizations, the colors are too whitewashed to be distinguished. This limit becomes much greater when the eye is tired and when the object observed does not have uniform brightness and hue. However, this type of polariscope lends itself poorly to precise measurements. If one tries to cancel the polarization by rotating

a pile of plates, the exact instant when the hues cease to be different is poorly defined. When exact compensation is finally observed, the images appear to the eye instantly tinted by colors complementary to those observed just before. These drawbacks led me to discard its use.

The Cornu Polarimeter

This device has a diaphragm with a rectangular opening which is illuminated by the light under study. At the opening a birefringent prism gives two contiguous images whose brightnesses can be made to vary with a Nicol prism. Since the eye can distinguish between two extended sources whose brightnesses differ by more than 1%, it must be possible to equalize, with the same precision, the fields of the Cornu photopolarimeter so as to detect ratios of polarized light down to 1/2%.

This result can be obtained in the laboratory, but it is necessary first to carefully eliminate the essential systematic errors which appear when:

1. The eye of the observer is not perfectly centered on the pupil of the instrument (the two beams originating from the birefringent prism, separated from each other when they enter the eye, go through unequal absorptions).

2. The aperture of the polarimeter is not completely uniformly illuminated. In the case of planets this last condition is almost impossible to meet as soon as the images become unsteady and the sensitivity of the instrument becomes much smaller than its theoretical value.

These disadvantages, together with the necessity of isolating the region to be studied with a diaphragm, make the Cornu instrument inadequate for the proposed goal.

The Savart Polariscope

The Savart polariscope consists of two quartz plates cut at 45° from the optic axis. These two plates are put together in such a way that their principal sections are mutually perpendicular. They are followed either by a Nicol or by a tourmaline which act as the analyzer. The Savart polariscope is mounted, just as the Arago polariscope, on the telescope eyepiece, and it gives linear fringes at infinity which appear on the planet. It is also a more sensitive instrument. The fringes appear immediately when the increasing ratio of polarized light reaches 1%, and their visibility increases sharply. As we will see later, this last property permits the construction of a very sensitive polarimeter.

The New Polariscope

After having established my choice for a polariscope of the Savart type, I first tried to improve this device with the help of the following considerations:

In order that the visibility of the fringes which appear on a planet source be maximum, it is necessary that three or four fringes be simultaneously observed. These fringes must therefore be fine without, however, having a separation of less than 6 to 8 minutes. In addition, the image of the source upon which the fringes appear must have a sufficient apparent brightness, at least be equal to a few thousandths candle per cm^2 (1). The polariscope must be as well illuminated as possible, in order to permit the use of high magnifications and to consequently study small parts of the planetary surface. These requirements have led me to the construction of the instrument described below.

Principles

The instrument is made of two identical calcite plates cut parallel to a cleavage plane and mounted with crossed principal sections. The analyzer is a calcite-glass birefringent prism whose principal section bisects that of the plates. When a source of light polarized along the plane bisecting the principal sections of the plates is observed through this system, the ordinary image and the extraordinary image analyzed by the birefringent prism contain one set of fringes each: a set with a white center and a set with a black center. The prism is cut in such a way that its edge is parallel to the fringes and its angle is such that it produces a splitting equal to half the fringe spacing in yellow light. The two systems of fringes are thus superimposed with coincident maxima and minima of light.

Advantages

This instrument has the following advantages: It permits all the light to pass through and produces images twice as bright as the Savart polariscope equipped with a Nicol, and has a field as wide as the field of the Savart polariscope equipped with a tourmaline. Made of calcite, it yields very fine fringes no thicker than a few millimeters. The eye can therefore be placed very close to the instrument pupil and can see the whole field of the eyepiece. The visibility of the fringes is little affected by unevenness of the brightness between the various parts of the planet. Suppose, for example, that a bright fringe is projected on a few spots bright enough to reinforce its brightness. Because of the birefringent prism, this action is compensated by the presence of a second image of these spots on one of the two adjacent dark fringes. The aspect of the fringes is not drastically modified when the plane of polarization of the incident light is rotated by 90°. This new situation is symmetrical with the first. This circumstance is also favorable to the goal we have in mind.

Construction

I have constructed three polariscopes based on these principles. The one best suited to the study of planets and which has almost exclusively been used throughout my work has the following characteristics:

(1) M. L. Santon has drawn similar conclusions. Diplome d'Etudes Superieures, 1928.

Thickness of each of the two calcite plates: 1.4 mm.

Fringe separation in yellow light: 10'.

Splitting of the birefringent prism: 5'10". Because of the low value of this angle the two images of the source are almost completely unseparated, even when the smallest patches are observed, because measurements cannot be made on details covering less than two to three fringes.

The birefringent prism consists of a calcite prism cut at an angle of 56' from a cleaved plate and made achromatic by glass. Its optic axis makes an angle close to 45° with the faces, and is oriented such that the image separation increases from one edge of the field to the other, together with increase in fringe separation. Thanks to this artifice, however secondary, the fringes maintain their maximum sharpness to the very edges of the field (1).

The New Polarimeter

The polariscope which I have just described, would have had an insufficient sensitivity if used alone, regardless of its advantages which greatly facilitate observations and slightly increase their precision. In fact, the fringes obtained with it cease to be visible with certainty when the ratio of polarized light becomes less than 1%. I was able to study weaker polarizations by adding a polarimeter which I will describe in detail below.

Principle of Operation

The principle of operation of the polarimeter consists in slightly polarizing the light rays which go through the polariscope in a plane alternately parallel and normal to the principal section of its analyzer. Because of this artifice the fringes become more visible and this allows the observations to be pursued. Assume that the light under study is completely natural or that it is polarized at 45° from that principal section: the fringes then keep constantly the same intensity. Suppose, on the contrary, that the light is slightly polarized parallel or normal to the analyzer principal section: this polarization, too weak to produce by itself an observable effect, is added to the one which is artificially created or is subtracted from it, thereby revealing its existence by alternately reinforcing or weakening the fringe intensity. The method consists in appreciating the equality or inequality of two weak contrasts.

---

(1) I must add that in May 1927, Mr. Fabry kindly lent me a relatively old polariscope which he found at the laboratory of the Faculté des Sciences. It is made up of two quartz Savart plates and a quartz Wollaston prism analyzer. The fringe separation is 30' and the prism splitting is 45' or one and a half times that value. The dark fringes are purple instead of black. I was not able to find either the author or the description of this device and was unaware of its existence when I did my work.

Sensitivity

It is evident that ratios of polarized light very much smaller than 1% can be detected by this method. Suppose, as an example, that the ratio of polarized light is 3/1000. Add to this a ratio of 9/1000 and the result is 12/1000, and the fringes are easily visible. Now subtract these two ratios: the remainder is 6/1000 and the fringes become totally invisible. We can conceive that polarizations very much less than 3/1000 can still appreciably vary the intensity of the fringes in this manner.

Construction

A description of the polarimeter, whose principles were described above and which enabled me to perform all the observations mentioned in this work, follows. It has a tube A (Fig. 1) which carries at one end the eyepiece O of the astronomical telescope. O supports the fringe polariscope P just described. The tube A slides in a tube B, secured to the telescope, for focusing. It can also rotate around its axis which coincides with the optic axis of the instrument, and its position is indicated by a graduation in degrees C. In addition it has two flat celluloid plates L_1 and L_2 (1). The first one can rotate around the axis DE. The angle between the normal to this plate and the telescope axis is shown by the pointer F, movable on the sector G which is graduated from 0 to 65°. The second plate can rotate around the axis HI which is mounted on a third tube J which in turn can rotate inside the first tube. This rotation is obtained by pushing shaft K with the finger. Shaft K goes through a slot M cut out from the tube A and adjusted such that the tube J rotates a quarter of a turn only, the axis HI being, in its extremum positions, parallel or normal to the axis DE. The knob N, mounted on the axis HI, affords a free inclination of the plate L_2 or enables the observer to stop it in a plane normal to the axis of the telescope, by means of a suitably located stop. The polariscope is contained in the eyecup which is screwed onto the eyepiece O and has on its periphery several notches. The spring R falls into these notches in order to secure the polariscope in a position such that the plane of the fringes is either parallel or normal to the axis DE of the plate L_1.

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(1) For the first series of measurements these plates were made of flat glass plates one millimeter thick. They had the disadvantage of giving spurious images by double reflection of the rays on their faces. These images coincided with the principal image when these plates were fairly normal to the beam. Conversely, the separation increased when the angle of incidence increased. The polarizations found in each case were not the same and differed by approximately 1/20 of their respective values. To avoid this trouble I have replaced the glass plates by celluloid films having 1/100 mm thickness. These were obtained by evaporation of a solution of celluloid in amyl acetate on a horizontal flat glass plate. These films are then stretched by gluing them on a frame made of a glass plate bored with a large hole. Even under very oblique incidence a flat prepared in this way gives only one image, either by reflection or by transmission. It does not appreciably absorb light. It seems perfectly isotropic, even though it behaves in reality like a negative uniaxial crystal whose optic axis is normal to its plane. At 60° incidence the birefringence is close to 0.012 yellow wavelengths. This weak birefringence does not perturb the measurements at all.

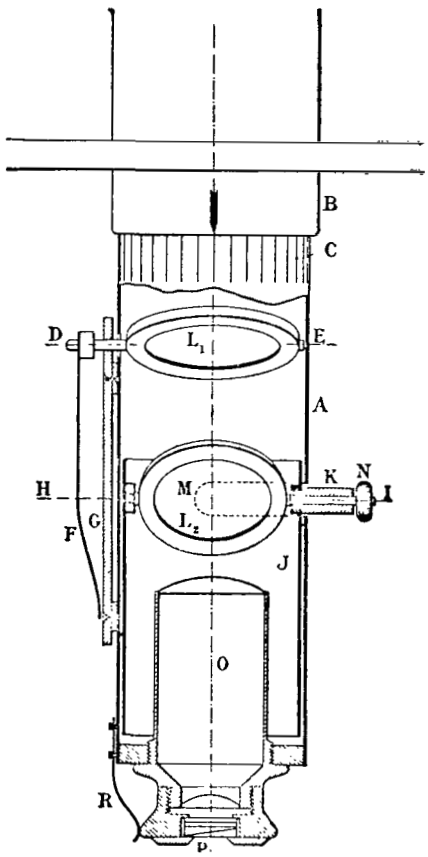

Figure 1.

Operation of the Instrument

Suppose for example, that light from the planet under study is partially linearly polarized. The series of operations to perform are the following. Make the plate L_1 normal to the telescope axis. Direct the telescope on the planet and operate the tube A to bring the image at the center of the eyepiece field and at infinity. Make the fringes of the polariscope appear on the planet by giving a sufficient inclination to the plate L_2. Rotate the tube J in both directions to have the plate L_2 take its two right-angle positions. The fringes have then a constant intensity only if the light is natural or if it is polarized at 45° to their directions.

Determination of the Plane of Polarization

In order to determine the plane of polarization, orient the tube A so that the fringe intensity is the same for the two positions of the plate L_2, then rotate it by 45°, in a direction such that the

fringes have their minimum intensity when the axes of the two plates are parallel. The plane of polarization sought is perpendicular to the axis of the plate L_1. Its direction is given by the circle C.

Measurement of the Ratio of Polarized Light

In order to measure the ratio of polarized light leave the tube A in the position it occupies, then rotate the plate L_1 until the one quarter turn rotations of the tube J do not modify the fringe intensity. The angle of incidence as read on the sector G gives the ratio of polarized light by means of a table which can be calculated from Fresnel's formulas (we shall perform this calculation later). When the direction of the plane of polarization is known in advance, the ratio of polarized light can be obtained by suitably orienting the instrument with the circle C.

Another Method That Gives Both Quantities Simultaneously

The following method allows simultaneous measurement of the position angle of the plane of polarization and of the ratio of polarized light. It consists of compensating the polarization to be determined by orienting the polarimeter successively in two directions 45° apart. Let P be the unknown ratio of polarized light, α and β the angles between the plane of polarization and the chosen two directions. The inclination of the compensating plane gives, in the first case, a polarization P, such that

$$P_1 = P \cos 2\alpha \tag{1}$$

and in the second case a polarization P_2 such that

$$P_2 = P \cos 2\beta = P \sin 2\alpha \tag{2}$$

from which

$$P^2 = P_1^2 + P_2^2$$

and

$$\tan 2\alpha = \frac{P_2}{P_1}$$

Formula (1) can be proved as follows: Let OX and OY (Fig. 2) be the axes of the calcite plates of the polariscope, OX' and OY' the axes of the analyzer. Suppose that the incident light is completely polarized and has vibrations along OA. Let β be the angle between OA and OX, α the angle between OA and OY. Consider first the vibrations proceeding along OX'. Their amplitude results in time from the vibrations OB' and OC' which are obtained by projecting on OX', the projections OB and OC of the incident vibration OA on OX and OY. This amplitude is

$$A_{x'} = \sqrt{\frac{OA^2}{2} \sin^2 \beta + \frac{OA^2}{2} \cos^2 \beta - OA^2 \sin \beta \cos \beta \cos \varphi}$$

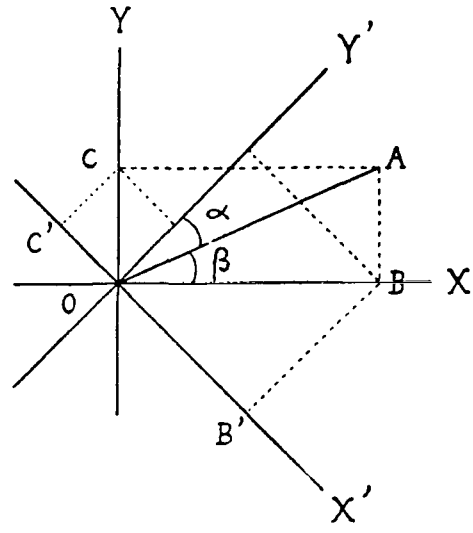

Figure 2.

where ϕ is the phase difference introduced by the plates of the polariscope and varies with the distance to the center fringe.

Along OX' the intensity is

$$I_{x'} = \frac{OA^2}{2}(1 - \sin 2\beta \cos \varphi)$$

or

$$I_{x'} = \frac{OA^2}{2}(1 - \cos 2\alpha \cos \varphi)$$

Along OY' we have, similarly

$$I_{y'} = \frac{OA^2}{2}(1 + \cos 2\alpha \cos \varphi')$$

Because the birefringent prism splits the directions of the two incident rays that come out together, they satisfy the condition

$$\varphi' = \varphi + \pi$$

We therefore have

$$I_{y'} = \frac{OA^2}{2}(1 - \cos 2\alpha \cos \varphi)$$

The total intensity is therefore

$$I = OA^2 (1 - \cos 2\alpha \cos \varphi) = I_0 (1 - \cos 2\alpha \cos \varphi)$$

where I_o is the incident light intensity.

Let I_1 and I_2 be the minimum and maximum light intensities, respectively, with ϕ being variable. I shall define the fringe visibility as the following ratio

$$V = \frac{I_2 - I_1}{I_2 + I_1}$$

where

$$I_2 = I_0 (1 + \cos 2\alpha)$$
$$I_1 = I_0 (1 - \cos 2\alpha)$$

We therefore have:

$$V = \frac{2 \cos 2\alpha}{2} = \cos 2\alpha$$

(Note that the bright fringe intensity is twice that of the source.)

If the incident light had a ratio P of polarized light, with I_o as the incident light intensity, we would have

$$I_2 = PI_0 (1 + \cos 2\alpha) + (1 - P) I_0$$
$$I_1 = PI_0 (1 - \cos 2\alpha) + (1 - P) I_0$$

and

$$V = \frac{2P \cos 2\alpha}{2} = P \cos 2\alpha$$

The fringe aspect and the inclination of the plate which compensate the polarization are the same only if light is polarized along the fringe plane; the ratio being

$$P' = P \cos 2\alpha.$$

Study of Elliptical Polarization

The same polarimeter can analyze, by Sénarmont's method, any elliptically polarized light, even when the latter is mixed with a greater proportion of natural light. If the ellipticity is very weak, the major axis of the ellipse and the polarized light ratio are directly found by the method described above. If the ellipticity is not too weak, a thick birefringent plate (made of quartz, for example) must be mounted on the polarimeter with one of its axes parallel to the plane of incidence

of the compensating plate L_1. Under these conditions, when working with white light, an elliptically polarized light acts on the instrument as if it were linear and partially polarized; the plane of polarization being perpendicular to the major axis of the ellipse. It then becomes easy to determine the direction α_1 of the major axis by the above method in order to obtain the plane of polarization of a linear vibration. The measurement of ellipticity includes the following steps. Determine the direction α_1 of the plane of polarization. Have a quarter-wave plate placed in front of the whole system, with one axis parallel to the found direction α_1. Read the new direction α_2 of the plane of polarization. Interchange the axes of the quarter-wave plate. Read the direction α_3 of the plane of polarization a third time. The ratio of the axes of the ellipse is equal to

$$\tan \frac{\alpha_2 - \alpha_3}{2}$$

The sign of this ratio gives an indication of the direction of rotation of the elliptically polarized light, and the ratio of this light can be directly measured for one of the two positions of the quarter-wave plate. This method permits therefore an easy determination of all the elements belonging to a given polarized light.

In measuring the light from celestial bodies I have never had to measure high ellipticities. It was therefore unnecessary to add a quartz plate to the polarimeter. I simply mounted a tube supporting the quarter-wave plate on the polarimeter end facing the objective.

This plate is held by a hinge; it can therefore be folded out of the way to determine the major axis of the ellipse, or can be placed perpendicular to the beam to measure the ellipticity. The tube in which it is mounted can rotate around the axis of the polarimeter. Two stops limit its rotation to 90° and permit interchange of the axes of the quarter-wave plate. In order that these may be substantially parallel to those of the ellipse, the positions of the stops are adjusted with respect to the direction found for the major axis.

Precision of the Measurements

All these measurements can have a high degree of precision provided the plate L_2 of the polarimeter is inclined with an angle just sufficient to insure the visibility of the fringes. Experience shows that under these conditions, and when the brightness of the source is sufficient, a ratio of linearly polarized light of 1% starts to produce a noticeable asymmetry. One can therefore compensate and measure small ratios of linearly polarized light to within 1/1000. The position angle of the plane of polarization is then defined with the precision given by Equation 2. When the polarimeter is rotated until the fringes are established, its principal plane makes an angle with the plane of polarization sought, such that

$$P \cos 2\alpha \leqslant \frac{1}{1\,000}$$

where P is the ratio of polarized light.

The maximum error $\Delta\alpha$, encountered when assuming that $\alpha = 45°$, is given by:

$$P \cos 2 \left(\frac{\pi}{4} + \Delta\alpha\right) = \frac{1}{1\,000}$$

therefore

$$P \sin 2\,\Delta\alpha = \frac{1}{1\,000}$$

When P is not very small, we have, approximately

$$\Delta\alpha = \frac{1}{2\,000\,P} \tag{3}$$

The plane of polarization of a ray containing 1% of polarized light can be measured within 3°. In the case of a highly elliptical vibration this position of the major axis can be determined with the same precision and the ratio of polarized light can still be obtained within 1/1000. The ellipticity being given by

$$E = \tan \frac{\alpha_1 - \alpha_2}{2}$$

or, approximately

$$E = \frac{\alpha_1 - \alpha_2}{2}$$

We have

$$\Delta E = \frac{1}{2\,000\,P} \tag{4}$$

The probable error is, approximately,

$$\frac{1}{5\,000\,P}$$

We can therefore detect, in a ray containing 1% of polarized light, the ellipticity of a vibration whose minor axis is equal to 1/20 of the major one.

Calculation of the Ratio of Polarized Light

This calculation will be made, using Fresnel's formulas, by taking into consideration the rays which have gone through an even number of reflections on both faces of the compensating plate. Assume that these cannot be separated from the direct beam and that they are not appreciably absorbed, which is always the case with the celluloid plates employed. Let an incident ray of natural light fall on the plate at an angle of incidence i. Let r_n and r_p be the reflecting powers of one of the faces of the plate when the vibrations are normal or parallel to the plane of incidence, respectively. In the first case the fraction transmitted through the plate is

$$\theta_n = (1 - r_n)^2 (1 + r_n^2 + r_n^4 .....)$$

or

$$\theta_n = \frac{(1 - r_n)^2}{1 - r_n^2} = \frac{1 - r_n}{1 + r_n}$$

Similarly, in the second case the fraction transmitted is

$$0_p = \frac{(1 - r_p)^2}{1 - r_p^2} = \frac{1 - r_p}{1 + r_p}$$

If the incident light is natural, it has, after having traversed the plate, a ratio of polarized light equal to

$$P = \frac{0_p - 0_n}{0_p + 0_n}$$

By replacing θ_n and θ_p with the values obtained before, we find

$$P = \frac{r_n - r_p}{1 - r_n r_p}$$

Fresnel's formulas give

$$r_n = \left(\frac{\sin (i - r)}{\sin (i + r)}\right)^2 \qquad r_p = \left(\frac{\text{tg } (i - r)}{\text{tg } (i + r)}\right)^2$$

Together with the preceding formula they enable P to be calculated as a function of i and of the index n of the plate. The first two columns of Table 1 were calculated in this way, by taking, for the index n of the celluloid compensating plate, the value of 1.511, which was measured with the Pulfrich refractometer using the D line. The two columns give the ratio of polarized light P in thousandths, as a function of the angle of incidence i, expressed in degrees.

Calibration of the Polarimeter

The reflecting powers of transparent media do not always have the values found from Fresnel's formulas. This is why I have tried to verify the exactness of Table 1 by measuring, with my polarimeter, known ratios of polarized light. I have used the following method, due to Cornu. The movable platform of a goniometer, whose axis has been made to lie horizontally, has at its center a source of completely polarized light consisting of a diaphragm illuminated by a ground-glass incandescent lamp followed by a Nicol. The rays emitted along the goniometer axis pass perpendicularly through a quartz plate which is 4 mm thick and is cut parallel to the crystal optic axis. From this plate partially polarized rays emerge along a plane parallel or perpendicular

TABLE 1
Thin Celluloid Plate of 1.511 Index

I	P	P'	I	P	P'	I	P	P'	I	P	P'
0	0.00	0.00	18	11.3	11.6	36	50.5	52.0	54	135.8	139.9
1	0.04	0.04	19	12.6	13.0	37	53.8	54.4	55	142.4	146.7
2	0.13	0.13	20	14.0	14.4	38	57.2	58.9	56	149.2	153.7
3	0.30	0.31	21	15.5	16.0	39	60.8	61.6	57	156.3	161.0
4	0.53	0.55	22	17.1	17.7	40	64.5	66.5	58	163.6	168.5
5	0.84	0.87	23	18.8	19.4	41	68.4	70.5	59	171.1	176.2
6	1.20	1.24	24	20.6	21.3	42	72.5	74.7	60	178.8	183.1
7	1.64	1.69	25	22.5	23.2	43	76.7	79.0	61	186.7	192.3
8	2.15	2.21	26	24.5	25.2	44	81.1	83.5	62	194.8	200.7
9	2.70	2.78	27	26.6	27.4	45	85.7	88.3	63	203.1	209.2
10	3.31	3.41	28	28.8	29.6	46	90.5	93.2	64	211.6	218.0
11	4.05	4.17	29	31.1	32.0	47	95.5	98.3	65	220.3	226.9
12	4.88	4.93	30	33.5	34.5	48	100.6	103.6	66	229.2	236.1
13	5.75	5.92	31	36.0	37.1	49	105.9	109.1	67	238.1	245.3
14	6.72	6.92	32	38.6	39.8	50	111.4	114.8	68	247.2	254.6
15	7.74	7.97	33	41.4	42.6	51	117.2	120.7	69	256.3	264.0
16	8.86	9.12	34	44.3	45.6	52	123.1	126.8	70	265.6	273.6
17	10.02	10.32	35	47.3	48.7	53	129.3	133.2	71	274.8	283.1
18	11.29	11.63	36	50.5	52.0	54	135.8	139.9	72	283.9	292.4

I: Angle of incidence expressed in degrees.
P: Ratio of polarized light expressed in thousandths, as calculated from Fresnel's formulas.
P': Ratio of polarized light, corrected from the calibration curve of Fig. 3.

to the optic axis. The ratio is $P = \cos 2\alpha$, where α designates the angle between this axis and the Nicol principal section (1).

(1) In fact, the incident vibration is divided into two polarized vibrations when it enters the quartz plate: one parallel, the other perpendicular to the optic axis. Because of the great thickness of this plate, the vibrations pass through a sufficient amount of retardation so that they do not set up any visible interference pattern with white light. Their intensities are therefore simply added. According to Malus' law, they are respectively proportional to $\cos^2\alpha$ and to $\sin^2\alpha$. The ratio of polarized light is therefore

$$P = \frac{\cos^2 \alpha - \sin^2 \alpha}{\cos^2 \alpha + \sin^2 \alpha} = \cos 2\alpha$$

If the quartz plate does not have a suitable thickness, spurious sets of fringes can form near the principal set of fringes and they disrupt the measurements. This phenomenon appears when the quartz plate introduces a path difference either small or close to the path difference between the rays directly crossing one of the celluloid plates of the polarimeter and the rays which go through two reflections on its faces. I have tried a 2 mm thick quartz and this gave spurious fringes. The 4 mm thick quartz did not lead to any phenomenon of this sort.

The angle α is given to within a constant by the goniometer circle. Its zero was obtained by analyzing the light emerging from the quartz with a Nicol, and by marking on the circle the position of the Nicol which gave the best extinction. The quality of the extinction and the precision of this determination varied greatly, depending upon the quartz sample tested. I have checked the zero by looking directly for the value of α corresponding to zero polarization.

I have analyzed the light emerging from the quartz with the polarimeter. This polarimeter was preceded by a simple lens which replaced the objective of the astronomical refractor and which formed an image of the diaphragm at the center of the eyepiece field.

The results are given on Table 2, in which we have mentioned the following: the angle α read on the goniometer circle, the corresponding angle of incidence i as given by the polarimeter circle, the value for cos 2α expressed in thousandths and the ratio of polarized light P expressed in thousandths, deduced from the angle i by means of Table 1.

TABLE 2
Polarimeter Calibration Curve

$\propto$	I	cos $2\propto$	P	$\propto$	I	cos $2\propto$	P
44°58'5	5°0	0.9	0.8	43°23'5	37°2	56.1	54.5
44 56.8	7.2	1.8	1.8	43 13.5	38.5	61.9	59.0
44 53.5	11.0	3.8	4.1	43 3.5	40.1	67.7	64.9
44 46.8	15.1	7.7	7.9	42 53.5	41.5	73.5	70.5
44 40.2	17.4	11.5	10.5	42 43.5	43.1	79.3	77.1
44 33.5	20.9	15.4	15.4	42 23.5	45.5	90.9	88.1
44 26.8	22.9	19.3	18.6	42 3.5	48.0	102.5	100.6
44 20.2	25.4	23.1	23.3	41 47.0	49.6	112.0	109.2
44 13.5	27.1	27.0	26.8	41 23.5	51.7	125.6	121.3
44 3.5	29.8	32.9	33	41 3.5	53.5	137.2	132.6
43 53.5	31.7	38.7	37.8	40 47.0	55.0	146.6	142.4
43 43.5	33.4	44.5	42.6	38 47.0	63.8	215.3	209.9
43 33.5	35.5	50.3	48.9	37 17.0	69.2	266.1	258.2

$\propto$: Angle between the polarizer principal section and that of the quartz.
I: Angle of incidence for the celluloid plate, corresponding to zero polarization.
P: Corresponding ratio of polarized light, as calculated from Table 1.
The values of cos $2\propto$ and P are expressed in thousandths.
The last six values are the average of four measurements.
The others are the result of single measurements.

The straight line drawn on Fig. 3 gives the differences P – cos 2α as a function of P, and adequately represents the series of measurements. The celluloid plate polarizes light more than Fresnel's formulas seem to indicate and behaves as if it had an index of refraction of 1.523, instead of 1.511. The slope of the straight line represents the corrections for the calculated ratios

of polarized light. The latter must be multiplied by 1.03. The values corrected in this manner are given by the third column P' of Table 1; they have been used to calculate the ratios of polarized light in the present work. These ratios are defined in absolute value, with a precision greater than that of the measurements of polarization.

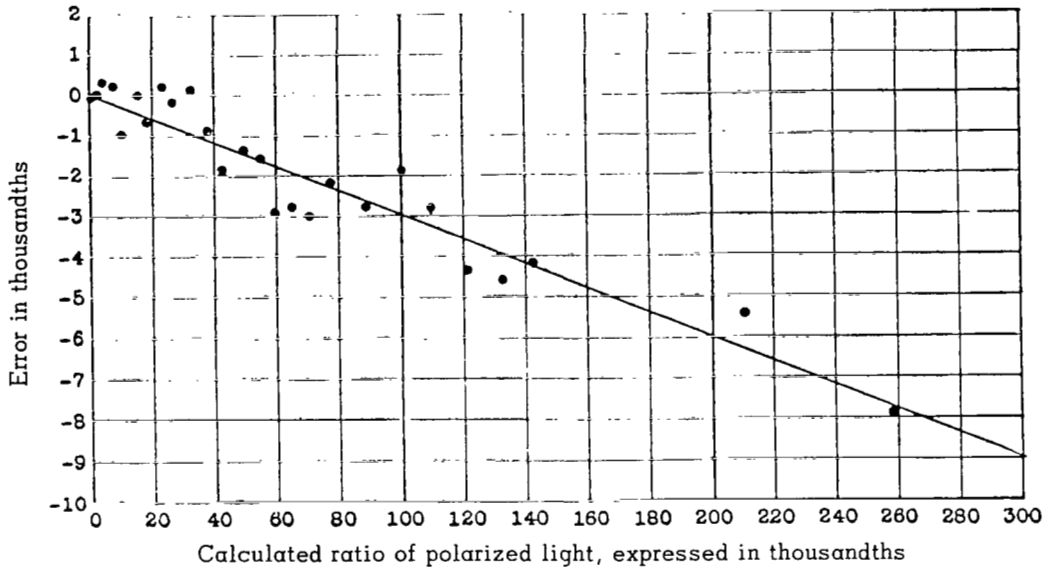

Figure 3. Polarimeter Calibration Curve

The Instruments Employed

The research on the polarization of light from planets was carried out by mounting my polarimeter on three instruments: the large refractor of the Meudon Observatory, a seven inch aperture refractor and a Cassegrain telescope. We shall examine the essential features which belong to these instruments.

The Large Refractor

The visual objective of the large equatorial of the Meudon Observatory measures 83 cm in aperture and 16 m in focal length. It has a very satisfactory achromatism for the red, yellow and green regions of the spectrum. The focus is highly stretched, however, in the extreme blue and the violet. The objective has excellently cut faces and, in addition, no permanent fault has been found in it. When atmospheric conditions are very favorable, it gives perfect images requiring a magnification of 800. I have examined the quality of the glass with polarized atmospheric light. For this, the telescope was directed at 90° from the Sun during the day, towards a point in the sky

completely free of clouds. The eyepiece was replaced by a Nicol oriented in such a way as to maximally attenuate the light. A gray cross was then apparent, with one of its arms directed towards the Sun. This cross was not completely regular in shape and its arms became distorted when the orientation of the objective with respect to the Sun was changed. The birefringence was therefore not very symmetrical. In order to estimate the errors that it could introduce, I have measured the polarization of the same point in the sky by placing the polarimeter alternately at the eyepiece end of the telescope or beside it. The polarization of the sky was close to 200/1000. Through the objective it was slightly reduced by an amount less than 2/1000. The polarizations measured with this instrument have therefore an error smaller than 1/100 their value. The figures found do not generally exceed 80/1000, and I have not corrected them.

The Small Refractor

To study the polarization of the planet as a whole or of a sizeable fraction of its disk, I have often preferred another refractor that is much smaller and easier to handle than the large refractor, and capable of rapid steering in cases of clear skies of short duration. Its objective measures 0.175 m in diameter and 2.60 m in focal length. The region of the spectrum where it is achromatic extends farther towards the blue, but, conversely, its secondary spectrum contains a little red. The surfaces are quite satisfactory in spite of the fact that an examination in the laboratory by the Foucault method reveals two zones which are of no appreciable influence on the resolving power. A magnification of 200 was necessary to observe the details of the image. The measurements were generally made with a lens magnifying 300 times. The objective, examined under polarized light, showed a dark, strong, and perfectly regular cross which remained unchanged when the objective was rotated around its axis. The tempering therefore was very strong, but fairly symmetric and it increased from the center to the edges.

I have measured the corrections to be applied to the results by pointing the refractor at a white and uniformly illuminated screen preceded by an inclined glass plate. The polarimeter was mounted on the eyepiece while I measured the polarization of that source, first without, then with the objective, by varying its orientation and by preceding the objective with circular diaphragms of 10, 12, and 14 cm apertures. As predicted, the polarization was perfectly independent of the orientation of the objective and varied only with its aperture. The ratio of the measured polarization, with and without the lenses, is:

1.012 with the 10 cm aperture.

1.067 with the 12 cm aperture.

1.119 with the 14 cm aperture.

1.246 with the total aperture.

The ratio of polarized light from the source was 104/1000. These figures are therefore known to less than 1/100. The refractor was always equipped with one of these diaphragms, preferably with the 12 cm one. I have made the corrections by multiplying the measured polarizations by the coefficient corresponding to the aperture employed.

The Cassegrain Telescope

A Cassegrain type telescope was useful for some measurements. Its large mirror had a diameter of 60 cm and a focal length of 2.10 m. The small hyperbolic mirror brings the total focal length to 14 m.

The perfect achromatism of the images does not necessitate the use of a color filter. On the other hand the reflection by mirrors, taking place at incidences near the normal (1), does not produce elliptical polarizations and does not modify the polarization to be measured.

The mirror surfaces of this telescope have a few irregularities and the images formed by it are not very fine and are always unsteady. This is why, in spite of its important qualities, I have preferred to work with the large refractor.

The Various Causes of Error

Marginal Polarization

The birefringence of the objectives which were studied in conjunction with the instruments is not the only source of errors. By examining the edge of the Moon or the edge of a planet with a refractor, I have often noticed the existence of a certain polarization at the outer edge. This polarization can be easily observed with the polarimeter which I have made or with a narrow fringe Savart polariscope. The fringes of the latter instrument, not visible on the disk, appear at the edge along a band generally smaller than one second in width. They disappear when their direction forms an angle of close to 45° with the edge.

I have studied these phenomena by observing the Moon, when its polarization is weak, with a polarimeter oriented at 45° from the plane of polarization of the lunar surface. These phenomena are: The marginal polarization extends within a band having a width which rarely exceeds one second. The polarization sometimes reaches the value of 20/1000 and seems to be independent of the instrument aperture, but varies strongly with the focusing. Inside the focus, the plane of polarization is perpendicular to the edge, outside the focus it is tangent to the edge. At the focus proper this polarization disappears if the secondary spectrum of the objective is carefully suppressed with an appropriate filter. If the filter is removed, the fringes appear inside the violet edge which borders the disk. The plane of polarization is then perpendicular to the edge. This phenomenon is of course of an instrumental nature, but so far I have been unable to explain it. To avoid this cause of error when using a refractor, I was always careful to suppress the secondary spectrum with an appropriate filter (2) and to focus with accuracy. Under these conditions no marginal polarization was apparent, regardless of image unsteadiness.

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(1) The aperture ratio for the large mirror being F/3.5, the angle of incidence of the rays at the edges is 1/14, or 4°5'. At the edge of the small mirror it is slightly smaller.

(2) These filters were made of a gelatin sheet glued to the Canada balsam between two thin plates and containing a large quantity of tartrazin and a very small quantity of green naphthol. The

Atmospheric Polarization

Our atmosphere cannot polarize light from a celestial body by refraction, since it does not reflect the rays. As discovered by H. Becquerel, however, it can rotate its plane of polarization. This rotation is maximum along the magnetic meridian and only reaches the value of 45' at 5° from the horizon. Since my observations were generally made at greater elevations, I have disregarded this phenomenon. When our atmosphere is not illuminated it does not noticeably modify the polarization from celestial bodies.

During the day this is quite a different matter. Here the brightness of the atmosphere can be compared to that of the planets and its very high polarization seems a priori, to make diurnal observations impossible. In fact, atmospheric light mixes with that under study and distorts the measurements. On the other hand, the planets Mercury and Venus pass too close to the Sun, during a great part of their phases, so that it becomes impossible to observe them during the night. I have therefore been led to search for a method which could eliminate the detrimental influence of our atmosphere. The solutions which I have thought worthy of consideration follow.

Compensation for Atmospheric Polarization

First Device

This procedure consists of covering the central part of the objective with a pile of photographic plates inclined at an incidence angle of 60°, approximately. These plates are taken from thin photographic plates whose faces are not exactly parallel and they deflect the rays from the planet which do not fall on the center of the eyepiece. Conversely, the plates direct the light coming from a neighboring part of the sky, onto the image of the planet, after having strongly polarized this light. A controlled shutter from the eyepiece location allows a variable number of rays to go through the pile and in this way controls the apparent polarization of the sky. This polarization appears to increase or decrease when the shutter is opened, according to whether the plane of incidence of the plates is almost perpendicular or parallel to that of the compensating plate of the polarimeter.

The following describes how the operation of the device works. Let the polarimeter be oriented along a certain direction. Let α be the angle between the plane of incidence of the compensating plate and the plane of polarization of the light from the planet, β the angle between this plane of incidence and that of the plane of polarization of the sky, P the ratio of polarized light from the planet (less the atmospheric light), P' that of the sky. These act on the device as the following polarizations, respectively

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proportion of these two coloring agents was adjusted depending upon the achromatism of the objective employed. Tartrazin completely removes the violet and the edge of the blue, and the green naphthol weakens the far red. These filters absorb very little light.

$$P_1 = P \cos 2\alpha$$
$$P_2 = P' \cos 2\beta$$

Let E_1 be the brightness of the planet without the atmosphere illumination, E_2 that of the sky. The apparent brightness of the planet is:

$$E_1 + E_2$$

and the component of apparent polarization along the principal plane of the polarimater is

$$P_3 = \frac{P_1E_1 + P_2E_2}{E_1 + E_2} \tag{5}$$

The observation of fringes on the planet and on the neighboring part of the field yields P_3 and P_2. The method consists in changing P_2 by modifying the shutter aperture until $P_2 = P_3$. P_3 is then measured and is equal to the sought value P_1.

In order to determine the plane of polarization of the planet it is only necessary to place the pointer of the compensating plate at the zero position and to simultaneously act on the polarization of the polarimeter and on the shutter aperture until $P_2 = P_3 = 0$. P_1 is then equal to zero and the principal plane of the polarimeter is oriented at 45° from the wanted plane of polarization. The shutter aperture must be adjusted at every measurement, because the transit of light cirrus clouds often leads to changes in the polarizations P_2 and P_3. When these quantities are close to one another at the start of observations it may become necessary to completely close the shutter or even to rotate the pile of plates one quarter of a turn during a whole series of measurements. This is inconvenient.

Second Device

In order to avoid such a disadvantage, I have replaced the fixed plates in the second case by plates mounted on a shaft which makes an angle of approximately 40° with the plate faces. This shaft is perpendicular to the axis of the refractor and makes an angle of approximately 45° with the plane going through the planet and through the Sun. By rotating it from the eyepiece end by means of a string, the incidence plane of the plates can be made to oscillate back and forth around the direction of the shaft, and this increases or decreases the polarization P_2.

The first device is necessary when the planet is far from the sky and strong atmospheric polarizations have to be compensated. The second one is more convenient for observations close to the Sun especially when the polarization of the planet is of the same sign as that of the sky.

Precision of the Measurements

Taking P_1 from Equation 5 we have $\quad P_1E_1 = P_3 (E_1 + E_2) - P_2E_2$

therefore

$$P_1 = (P_3 - P_2)\frac{E_2}{E_1} + P_3$$

The error on P_1 is

$$\Delta P_1 = \Delta P_3\left(1 + \frac{E_2}{E_1}\right) - \Delta P_2\frac{E_2}{E_1}$$

Let ΔP be the maximum error on P_3 and P_2, the maximum error on P_1 is

$$\Delta P_1 = \Delta P\left(1 + 2\frac{E_2}{E_1}\right)$$

The probable error is smaller. Suppose for example that $E_1 = E_2$, which gives $E_3 = 2E_2$ (apparent brightness of the planet twice that of the sky). ΔP being equal to 1/1000 we obtain

$$\Delta P_1 = \frac{3}{1\,000}$$

The probable error would therefore be 2/1000.

Precautions

To ensure that these methods give satisfactory results it is good practice to protect the objective of the refractor against sunrays so that scattering of the rays by the lenses may be avoided. Parasitic images of the Sun created by multiple reflections, and overheating of the interior of the tube are also to be avoided. In order to do this, I have extended the refractor at the objective end with a triangular bamboo support to carry a series of cardboard rectangular screens attached to one of the sides and perpendicular to the axis of the support. Their spacings increase from the objective so that the latter is always in the shadow of any one of them (1). With this precaution it is very easy to measure the polarization of Venus, as long as this planet is close enough to the Sun so that the polarization of the sky does not exceed 60/1000. When the distance from Venus to the Sun reaches 20°, light cirrus clouds, sometimes invisible, are sufficient to change the atmospheric polarization. The compensation must be constantly repeated and the operation done quickly.

Above 25° a bothersome phenomenon shows up. The visibility of the fringes on the sky depends upon eye accommodation. This phenomenon can be easily understood by examining the exit pupil of the refractor (image of the objective formed by the eyepiece). The rays emanating from its periphery and those which have traversed the pile of plates contain high enough amounts of polarized light, but these are equal to each other and of opposite sign. If the observer looks at infinity these two pencils of rays form on the retina two sets of complementary fringes which

(1) I have used supports of various sizes for the 0.175 m aperture refractor. The largest was 2.50 m long and permitted measurements as close as 4° from the Sun.

destroy each other. The first pencil covers a portion of the pupil much greater than the second. Consequently, if the observer accommodates his eye, the fringes given by the first pencil fade out much faster than those of the second, and, the set of fringes reappears. The eye is then tempted to accommodate again. This phenomenon leads to very difficult measurements; the compensation becoming a function of the extremely variable convergence of the eyelens. To reduce this difficulty it is sufficient to increase the magnification and to somewhat close down the objective. The visibility of the fringes then depends very little upon the eyelens convergence, and it becomes possible to accommodate.

With a magnification of 400 and an aperture of 120 mm, the brightness of the images is still sufficient and measurements on Venus are possible to about 40° from the Sun, in spite of the fact that the polarization of the sky is greater than 200/1000, or is approximately ten times that of the planet.

Automatic Compensation for Atmospheric Polarization

I finally tried to compensate the atmospheric polarization by the following device. Two identical calcite rhombs A and A' (Fig. 4) are glued with Canada balsam on each side of a quartz plate B cut parallel to the optic axis. Their principal sections are parallel and make an angle of 45° with the axes of the quartz. The whole set is inserted between two glass plates C and C' glued with Canada balsam (1).

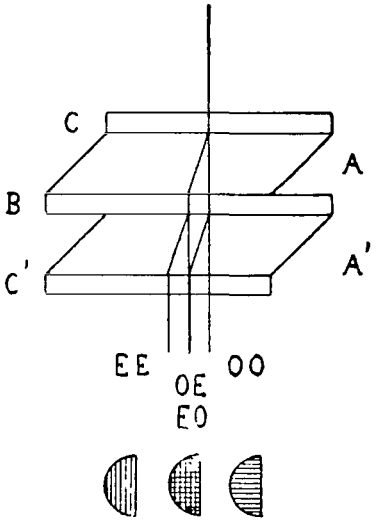

Figure 4. Automatic Compensation of Atmospheric Polarization

(1) Canada balsam has the property of eliminating reflection on the surface of the calcite pieces, which results in unequal dimming of the ordinary rays and the extraordinary rays.

This set is placed behind the eyepiece, between the latter and the polarimeter plates. It is oriented so that the principal sections of the calcites are parallel or perpendicular to the plane of incidence of the first plate. The first rhomb gives two images of the planet, which are completely depolarized by the quartz plate. Under these conditions the second rhomb gives four images: OO, OE, EO, EE. The second and third images are polarized in opposite signs and are superimposed (1).

Let P be the ratio of polarized light from the planet. Assume its plane to be parallel to the principal sections of the calcites. The central image has then a ratio of polarized light equal to P, but lying in a perpendicular plane. If the plane of polarization of the planet makes an angle α with the principal sections of the calcites, the polarimeter will read a ratio

$$P' = -P \cos 2\alpha.$$

If the sky is illuminated by the Sun, its light does not act on the polariscope, because the four images are superimposed and their polarizations cancel each other. It is therefore sufficient to make the measurements on the central image as if the sky light did not exist. A ratio of polarized light equal to that of the planet and a plane of polarization perpendicular to its own are thus obtained.

(1) It is necessary that this superposition be perfect, otherwise spurious polarizations can appear in the central image when the planet does not have a very uniform brightness. It is sufficient that the rhombohedrons be identical, that their four faces be parallel, and that their optic axes also be parallel. The adjustments can easily be made by observing a light spot placed behind the calcites with the microscope. The rhombohedrons introduce some astigmatism, but this does not disturb the measurements because it is exactly the same for both images OE and EO.

CHAPTER III. POLARIZATION OF LIGHT FROM PLANETS

GENERAL ASPECTS

Conditions of Illumination

Since the light from planets is composed of scattered sunrays its polarization should depend on the relative position of the Earth with respect to the Sun. In what follows I shall define this position with the help of the following two quantities:

1. The angle between the incident sunrays and the sunrays scattered towards the Earth (angular distance between Earth and Sun as seen from the planet), which I shall call the "angle of vision" and which will be designated by the letter V (1).

2. The position angle of the plane going through the observer, the planet and the Sun. I shall call this plane the "plane of vision" and its position angle (angle between the plane of vision and the meridian going through the planet, measured positive from 0° to 180° counterclockwise) will be designated by the letter X (2).

I have calculated these two quantities for each observation, with a precision of 5' for the large angles of vision, 1' for the small angles of vision, and 6' for the position angle of the plane of vision.

Calculation of the Angle of Vision

Case of a Planet

The Connaissance des Temps lists the heliocentric and geocentric latitudes β and β' and the longitudes λ and λ' of the planet.

The angle V sought is given by the formula

$$\cos V = \sin \beta \sin \beta' + \cos \beta \cos \beta' \cos (\lambda - \lambda')$$

When $\lambda - \lambda'$ is small, this formula loses its accuracy. Since β and β' never exceed 7°, I have used in this case the approximate formula:

(1) For the Moon and for the inferior planets, this angle can vary between 0° and 180°. For the superior planets this angle is limited to small values. Its maximum varies with the reciprocal of their distance to the Sun. It is 47° for Mars, 12° for Jupiter and only 6° for Saturn.

(2) These definitions were previously used by Soret, Annales de Physique et Chimie, Series 14, 188, p. 503.

$$V^2 = (\beta - \beta')^2 + (\lambda - \lambda')^2.$$

Similarly when $\lambda - \lambda'$ is close to π, we have, approximately

$$(\pi - V)^2 = (\beta + \beta')^2 + (\lambda - \lambda' - \pi)^2$$

Case of the Moon

Let α and δ be the right ascension and the declination of the Moon interpolated from the Connaissance des Temps for the time of observation. Since these data are relative to the center of the Earth, they must be referred to the site where measurements were made, and the following corrections should be added

$$\Delta\alpha = - \pi \cos \lambda \frac{\sin H}{\cos \delta}$$

and

$$\Delta\delta = - \pi \sin \varphi \cos \delta + \pi \cos \varphi \sin \delta \cos H$$

where π is the lunar parallax
H the hour angle of the Moon
ϕ the latitude of the observer
δ the declination of the Moon.

For Paris we take

$$\varphi = 48^{\circ}50' \text{and} \pi = 57'30'' \text{ (mean value)}$$

The formulas then become

$$\Delta \alpha = - 57'35'' \frac{\sin H}{\cos \delta}$$

$$\Delta\delta = - 43'5'' \cos \delta + 57'35'' \sin \delta \cos H$$

Let α_1 and δ_1 be the corrected values, α' and δ' the right ascension and the declination of the Sun. The angular distance E between the Moon and the Sun can be calculated from a formula similar to the one which was given for the planets

$$\cos E = \sin \delta_1 \sin \delta' + \cos \delta_1 \cos \delta' \cos(\alpha_1 - \alpha').$$

On Fig. 5 are shown schematically the positions M, E, S of the Moon, the Earth and the Sun. The angle of vision sought is the angle M. It is equal to π - E - S.

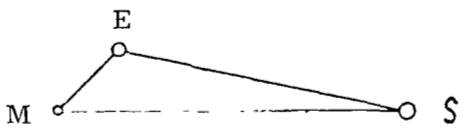

Figure 5.

On the other hand, the angle S is very small and is given by the formula

$$\sin S = \sin E \frac{ME}{MS}$$

or, approximately

$$S = 8'.40'' \sin E$$

therefore

$$I = \pi - V - 8'.40'' \sin E$$

When the measurements were relative to the whole Moon I have introduced a small correction in order to refer the angle V to the center of the crescent. For this it is only necessary to increase V by approximately 5'(1 - cos V).

When the measurements were made on a certain region, I drew an axis on the map of the Moon which went through its center and was normal to the direction of the sun. The correction sought was equal to the angular distance between the considered region and this axis; measured in a positive direction away from the Sun.

Case of the Lunar Eclipses

During an eclipse of the Moon, when the observed region is situated in the penumbra, one must take into consideration the deformation of the solar disk which is caused by the presence of the Earth. It is therefore easier to calculate the angles V and X at opposition with the help of a diagram such as that of Fig. 6, which is relative to the night of 28 to 29 January 1926. The center of coordinates is supposed to coincide with the center of the shadow cone of the Earth.

Let α and δ be the right ascension and the declination of the Moon, α' and δ' be those of the Sun. The curve drawn on the top part of the diagram was obtained by taking for each hour

$(\alpha - \alpha' - 180°) \cos \delta$ for abscissas, and

$\delta + \delta'$ for ordinates.

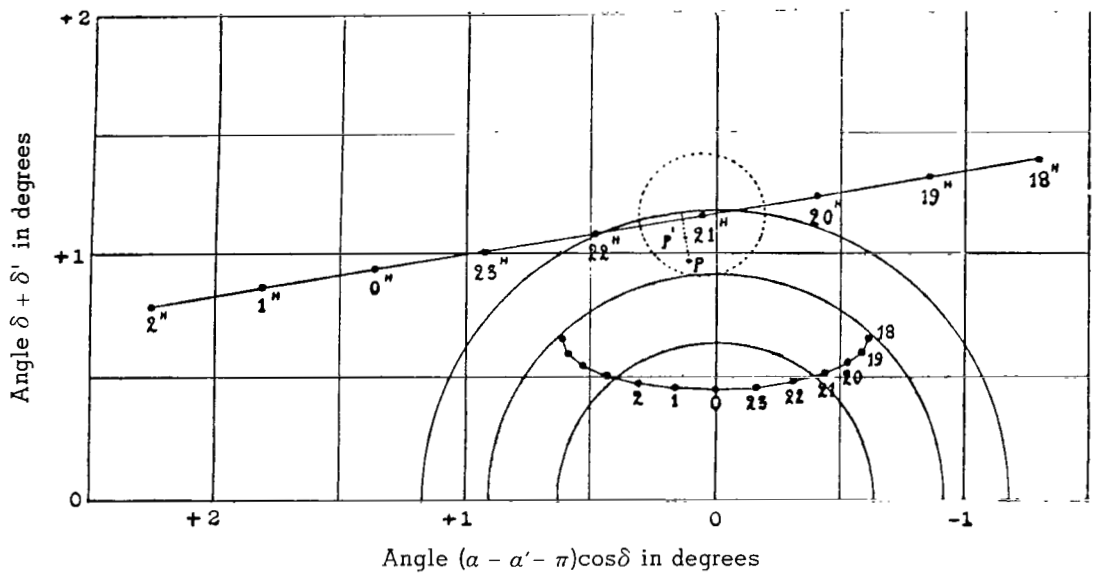

Figure 6. Trajectory of the Moon (Night of 28–29 January 1926)

The curve represents the trajectory of the Moon with respect to the center of the shadow cone 0. From 0 as center three circles were drawn of approximately 1°30', 2° and 2°30' diameters, respectively. They represent the umbra, the mean umbra and the penumbra, respectively. The trajectory described by the shadow of the point where the observer is situated is an ellipse which is tangent to the circle of mean umbra and whose points have

$$-\cos\phi \sin H \text{ for abscissas, and}$$

$$\sin\phi \cos\delta - \cos\phi \cos H \text{ for ordinates.}$$

Now place a suitably oriented transparent drawing of the Moon on the diagram, centered on the position which the Moon occupies at a certain hour. Then with a straight line join the point where the shadow of the observer is located at that time to a given region of the transparent drawing. The length of the straight line represents the angle of vision for that region. The angle which the line makes with the ordinate axis is equal to the position angle of the plane of vision. When the region under consideration is situated in the penumbra I have replaced on the diagram the projection point P by the point P' which is at midpoint between P and the circle of the penumbra, in order to approximately take into consideration the displacement of the center of the light source due to the Sun being partly hidden by the Earth.

Calculation of the Position Angle of the Plane of Vision

Let α and δ be the right ascension and the declination of the Sun, α' and δ' those of the planet. With the help of these coordinates, draw on the celestial sphere the positions S and P of

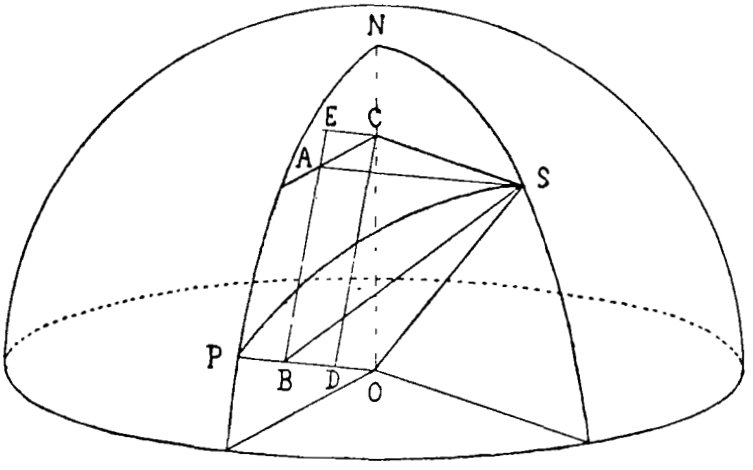

Figure 7.

the Sun and of the planet (Fig. 7). Let ON be the axis of the celestial sphere. Draw the meridians NS and NP and the great circle arc PS. The angle sought is the angle SPN. From S draw the perpendiculars SA and SB to the plane NOP and to the straight line OP. We have

$$\tan SBA = \frac{SA}{AB} = \tan SPN$$

Let C be the projection onto ON of S. The triangle SCA has

$$SA = SC \sin(\alpha - \alpha') = \cos\delta \sin(\alpha - \alpha').$$

From A and C draw the perpendiculars AB and CD to OP. From C draw the parallel to OP which crosses BA at E. We have

$$\begin{aligned} AB &= EB - EA = CD - EA \\ CD &= CO \cos\delta' = \sin\delta \cos\delta' \\ EA &= CA \sin\delta' = \cos\delta \cos(\alpha - \alpha') \sin\delta' \end{aligned}$$

therefore

$$\tan P = \frac{\cos\delta (\sin\alpha - \alpha')}{\sin\delta \cos\delta' - \cos\delta \cos(\alpha - \alpha') \sin\delta'} \tag{6}$$

or

$$\tan P = \frac{\sin(\alpha - \alpha')}{\operatorname{tg}\delta \cos\delta' - \cos(\alpha - \alpha') \sin\delta'} \tag{7}$$

When $\delta - \delta'$ and $\alpha - \alpha'$ are small, formula 6 gives:

$$\tan P = \cos \delta \frac{\sin (\alpha - \alpha')}{\sin (\delta - \delta')} = \cos \delta \frac{\alpha - \alpha'}{\delta - \delta'}$$

Similarly, when $\delta - \delta'$ is small and $\alpha - \alpha'$ is close to π, the coordinates of the antisolar point are $\pi + \alpha$ and $- \delta$ and the formula becomes:

$$\tan SPN = \frac{\pi + (\alpha - \alpha')}{-(\delta + \delta')} \cos \delta'.$$

Results

As we shall see later in this chapter, the light which comes from planets is most often polarized, as in the case of simple scattering, in a plane which is either parallel or perpendicular to the plane of vision. I shall take the polarization as being positive in the first case, negative in the second (1).

Every observation relative to the same planet will be indicated by a point whose abscissa is the angle of vision and whose ordinate is the ratio of polarized light with its proper sign. The curve drawn through those representative points will characterize the physical state of the planet under consideration. A comparison of curves belonging to two different epochs will show if this physical state has changed. Lastly, a plane of polarization which is neither parallel nor perpendicular to the plane of vision would reveal the presence of phenomena not associated with simple scattering.

Study of Solar Light

Before approaching the study of planets, we shall study the source which illuminates them. It is generally believed that the light from the Sun is not polarized. This conclusion was not verified to date with an accuracy greater than 1/100. I have frequently examined the surface of the Sun with my polarimeter equipped with a black lens and mounted on the 0.175 m aperture refractor. I have not found on this surface any trace of polarization. I have repeated these observations later with the help of a refractor of 20 mm aperture and with a thin glass plate mounted ahead of the polarimeter. The incident rays traversed the glass plate at an incidence of 10° and the plane of incidence was perpendicular to that of the first plate of the polarimeter. The whole system was directed towards the Sun and could easily rotate around the axis common to the polarimeter and to the refractor. Under these conditions the polarimeter measured a ratio of polarized light independently of its orientation, which remained close to 3.5/1000 to within 1/1000. The polarization of the Sun is therefore very much less than 1/1000 and must undoubtedly not reach a value of 2/ or 3/1000. It therefore cannot exert any influence on the results obtained on the planets. I have repeated these measurements on 6 and 7 August 1924 on the setting Sun, at 2°

(1) The same convention was adopted by Soret (Annales de physique et chimie, 14, 188, p. 503).

from the horizon, with a very clear sky. The measurements yielded polarizations less than 0.5/1000. Therefore the refraction of rays passing through the atmosphere is not accompanied by polarization of the light, as could have been predicted, and it is possible to correctly measure the polarization of planets as close to the horizon as atmospheric transparency permits.

The Moon

Conditions of Observation

The angle of vision of the Moon varies within wide limits because of the movement of our satellite around the Earth. However, at certain oppositions, this angle does not go below approximately 5° as a result of the inclination of the lunar orbit. An observer, situated at a certain location, sees the angle go to zero only during certain eclipses of the Moon (see original French p. 34). On the other hand, when the conjunction is approaching, the brightness of the crescent decreases much faster than Lambert's law would seem to indicate. In addition, the proximity of the Sun forces the observer to look into the dusk or the drawn light and the measurements become impossible when the angle of vision exceeds 160°. The large apparent diameter of our satellite, however, and the absence of any noticeable atmosphere on its surface, greatly facilitate the separate observation of various parts of its ground. I was able to take measurements between 0°21' and 159°26'.

Polarization of the General Light of the Moon

In order to ascertain the general character of the Moon and in order to subsequently facilitate its comparison with the planets, we shall first study the light from the Moon as a whole.

Experimental Apparatus

For this study the objective of the refractor was replaced by a lens of 18 cm focal length, located in the tube of the polarimeter such that one of its foci coincided with the outer face of the polariscope. The other focus location was occupied by a diaphragm of 8 mm diameter.

The polariscope was covered with a 4 mm diameter eyecup at the center of which a small image of the Moon was formed. The eye, when placed against this eyecup, received the whole light from our satellite, and one observed the fringes of the polariscope projected on the virtual image of the diaphragm located at infinity. When the angle of vision was less than 120°, the measurements could be easily made during the night, or any season.

When the angle exceeded this value, I was forced to make observations either during the spring equinox just after sunset, or during the fall equinox shortly before sunrise. The sky light was sometimes disturbing, and I was therefore careful to decrease it by substituting a thin foil for

the eyecup. This foil had a crescent shaped aperture that circled the image of the Moon. Because of this device, I did not need to compensate for atmospheric polarization, and I made a few preliminary measurements as soon as the Moon appeared to the naked eye. The resultant figures varied at first rapidly with the brightness of the sky and then became constant. Only then did I start the measurements proper.

When the angle of vision exceeded 150°, the crescent was very distant and the eye no longer received sufficient light. In this case, I located the polarimeter at the eyepiece end of the large Meudon refractor, by removing the lens and the diaphragm which were replaced by the 0.83 m objective. The image of the crescent was 16 cm in diameter, but its width was very small. In particular, during the nights of 6 April and 5 May 1924, it measured at its midpoint 6 mm and 3 mm respectively. I then made a series of measurements by successively observing the image of various segments of the crescent. Their polarizations were close enough so that it was sufficient to take their average.

The measurements of very small angles of vision were obtained during the eclipse of 8 February 1925, when the Moon had traversed the north part of the edge of the shadow.

Plane of Polarization

Sixty-one observations were made by this method. The plane of polarization was always found to be either parallel or normal to the plane of vision, to within a few degrees. According to the conventions established (French page 50), I have affixed to the ratios of polarized light the + sign in the first case and the – sign in the second.

Ratio of Polarized Light

The obtained results are summarized in Table 3. The curve A of Fig. 8, drawn in the direction of the arrow, shows how the ratio of polarized light varies during a lunation. The points belong to various lunations. It is seen that the polarization goes through the same values several times, except perhaps in the neighborhood of the quadratures where the libration seems to exercise a small influence. During those epochs the polarization reaches a maximum and its plane is parallel to the plane going through the Sun, as Arago and his successors noticed. The maximum is 66/1000 when the Moon goes through its first quarter and 88/1000 when the Moon is on its last quarter. This difference is due to the fact that the seas occupy an area approximately twice as large during the last quarter than during the first. The sudden drop which follows the last quarter coincides with the disappearance at the terminator of the darkest regions of Mare Nubium and of Mare Imbrium.

Around the new Moon, the polarization decreases and the two branches of the curve rapidly approach each other. Similarly around the full Moon, they become one curve below 35°.

TABLE 3
Moon: General Light

Date and Time				V	M	E	P	O
1922	7	July	2300	14°31' C	10	1.1	−10 *	17
	9		0000	4 34 C	10	0.6	− 7.7*	17
	8	August	2130	13 50 D	15	1.8	−11.8*	17
	9		2200	24 55 D	5	0.7	+ 2.5*	17
	2	November	2030	21 20 C	8	0.3	− 3.6*	12
	4		2200	4 30 D	13	0.5	− 8.5*	12
	31	December	2100	27 36 C	8	1.3	+ 6.6*	12
1923	1	January	1800	17 54 C	8	0.8	− 7.7*	12
	3		2100	10 49 D	8	0.9	−11.8*	12
	19	August	2000	82 29 C	6	1.2	+65.3	..
	20		2000	69 35 C	4	1.7	+57.5	..
	22		2000	43 56 C	4	0.2	+28.8	..
	23		2000	31 16 C	4	0.4	+ 9.2	..
	24		2000	19 09 C	1	...	6.4	..
	25		2000	6 48 C	3	0.4	10.2	..
	13	October	1800	132 11 C	3	1.1	+51.6	..
	14		1810	117 33 C	3	1	+61.8	..
	15		1915	103 54 C	4	0.8	+64.8	..
	16		2000	90 55 C	6	0.6	+65.2	..
	17		1800	80 15 C	4	0.8	+62.2	..
	19		1915	55 30 C	3	0.6	+40.6	..
	21		2100	29 25 C	5	0.4	+11.3	..
	22		1830	21 48 C	3	0.2	− 2.3	..
	26		2000	23 17 D	4	0.3	0.3	..
	28		2200	45 55 D	4	0.4	+33.2	..
	29		2140	57 0 D	4	0.4	+50.3	..
	30		2300	68 37 D	4	0.7	+67.6	..
	31		0000	80 34 D	11	2.5	+79.4	..
	3	November	0230	105 45 D	7	0.4	+88.0	..
	4		0545	119 13 D	3	1.8	+70.8	..
	5		0400	132 21 D	9	0.8	+59.3	..
	6		0500	146 27 D	9	1.0	+40.1	..
	12		1815	123 16 C	5	0.8	+57.5	..
	13		1715	110 45 C	4	0.8	+66.4	..
	16		1700	74 46 C	4	0.5	+60.3	..
	17		1800	63 7 C	4	0.3	+52.3	..
	10	December	1730	143 24 C	7	0.8	+41	..
	23		2130	8 28 D	5	0.3	−12.2	..
	24		2300	19 29 D	6	0.4	− 5.5	..
	28		2300	66 52 D	10	1.5	+64.8	..
1924	28	January	0100	75 10 D	5	1.5	+74.1	..
	29	February	0600	112 8 D	11	1.1	+87.8	..

TABLE 3 (Continued)

Date and Time			V	M	E	P	O
6	April	2000	151 55 C	4	1.0	+33 *	81
25		0300	76 42 D	8	0.6	+76.7	..
26		0400	89 46 D	4	0.8	+83.6	..
27		0330	109 28 D	6	1.6	+96.6	..
5	May	2000	159 26 C	3	0.6	+29.8*	81
1925 8	February	....	0 21	3	0.4	- 0.5*	12
..	.....	....	0 54	3	0.4	- 3.3*	12
..	.....	....	1 22	2	0.3	- 4.7*	12
1	July	2300	58 35 C	3	0.7	+48.4	..
3		2130	33 16 C	6	0.3	+13.9	..
5		2330	3 40 C	6	0.3	- 7 *	11
6		0200	2 33 C	4	0.2	- 5.5*	11
7	August	0000	35 3 D	5	0.3	+16.3	..
7		2200	47 28 D	5	0.5	+35.2	..
30		2200	40 15 C	5	0.2	+24.7	..
4	September	2130	28 28 D	5	0.5	+ 7.9	..
5		2100	40 56 D	4	0.2	+27.1	..
24	October	2100	24 5 C	9	0.9	+ 2.0*	8

V: Angle of vision.
M: Number of measurements.
P: Average ratio of polarized light expressed in thousandths.
E: Mean deviations of the different values of P from their averages.
The polarizations indicated with an asterisk are average values relative to different regions.
The last column, O, indicates the free aperture of the instrument (83 corresponds to the large Meudon telescope. The numbers smaller than 17.5 cm correspond to the 175 millimeter telescope. When there is no number, the corresponding polarization value was obtained with the apparatus described on (French) page 39.

Approaching full Moon, i.e., approximately two days before full Moon, when the angle of vision is 23°30', the polarization goes to zero and reappears a few hours later along a perpendicular plane. The polarization goes then to a negative minimum of -12/1000 for the angle of 11°, then tends fairly rapidly to zero to finally become zero at the same time as the angle of vision. After opposition, the same phenomena are reproduced in the reversed direction, in an absolutely symmetrical way. This inversion of the plane of polarization had never been observed before. Arago and his successors never observed any appreciable amount of polarization on the Moon below approximately 30°. The polarization is, however, significant for the angle of 10° and can easily be detected to 1° from the opposite direction to the Sun, where the polarization still exceeds 1/1000. We will find later, in other cases, a similar phenomenon.

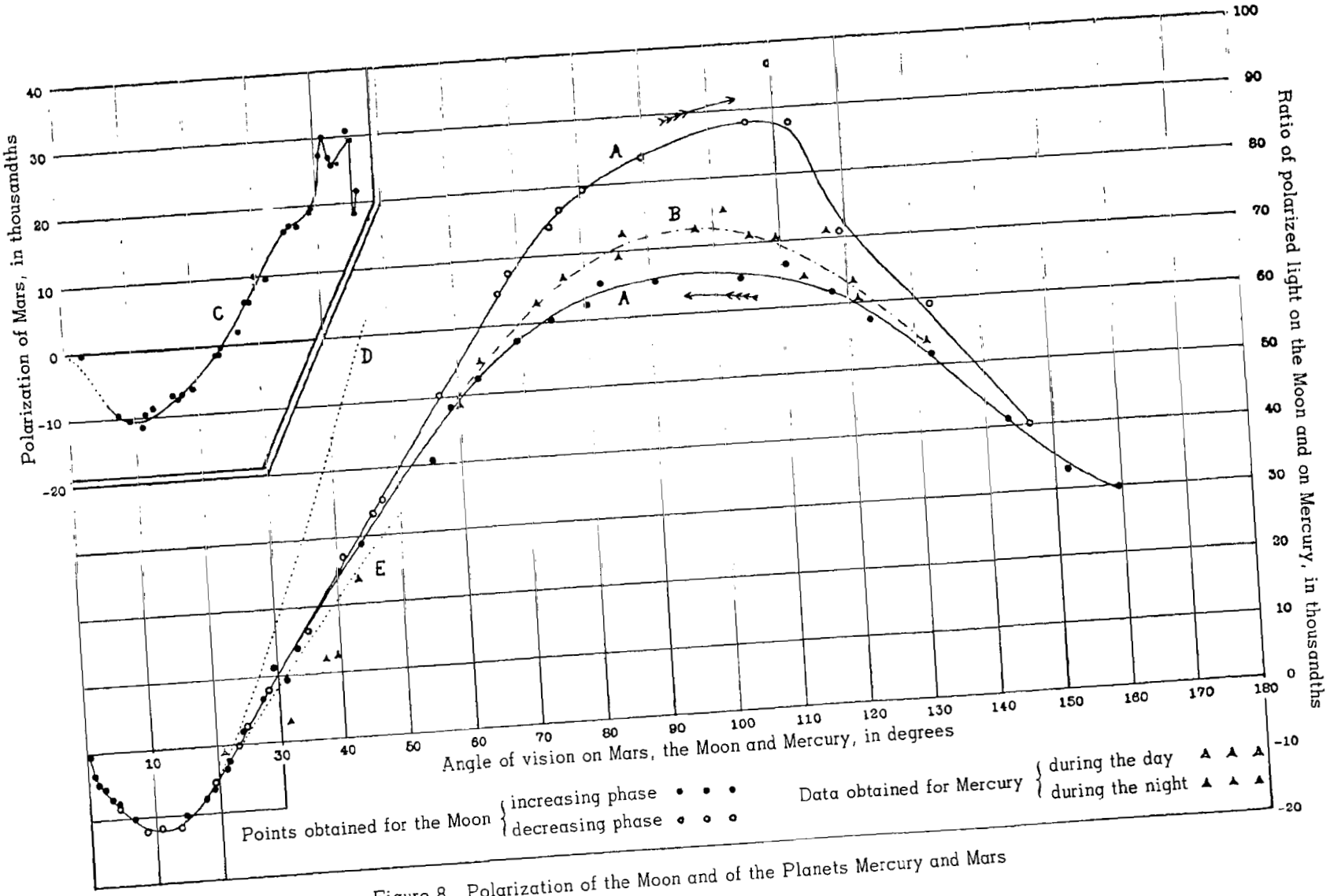
Polarization of Mars, in thousandths
Ratio of polarized light on the Moon and on Mercury, in thousandths
Angle of vision on Mars, the Moon and Mercury, in degrees
A
B
A
C
D
E
Points obtained for the Moon { increasing phase / decreasing phase
Data obtained for Mercury { during the day / during the night

Figure 8. Polarization of the Moon and of the Planets Mercury and Mars

Regional Study

Following the preceding results, the question arises whether the phenomena which were described at the beginning of this chapter apply to the whole Moon or whether the polarization is very different from one region to the next, and then whether the resultant of all these polarizations would be the observed curve. On the other hand, the study of lunar ground details must be of great help for analogically interpreting the results which are obtained by observing the other planets. This is what led me to undertake the study of the various regions of the Moon.

Plane of Polarization

We already know the plane of polarization of our satellite as a whole. The following experiment shows that it is the same at every point on the Moon. If the polarimeter is rotated by placing its compensating plate perpendicularly to a beam, a position is found such that the fringes keep the same intensity for the two positions of the comparator. This equilibrium, established for a certain region of the Moon, is maintained when the different points of the lunar surface are successively passed through the center of the field. I have repeated the experiment several times, for different phases of the satellite, without ever noticing any definite difference between any two regions.

Around the last quarter the method is more sensitive because the polarization is then maximum. On the clear regions, where the ratio does not exceed 50/1000, the plane can be defined as given by formula 3 of (French) page 19, to within $1/2000 \times 1/0.05$ or 1/100, i.e., to within 34 minutes. On the seas, where the polarization is much stronger, the precision is three or four times better.

The plane of polarization is therefore the same on the continents as on the seas, to within less than half a degree. It does not depend upon the orientation of the surface of the Moon with respect to the directions of the Earth and the Sun, as could have been supposed, but only depends upon the orientation of the plane of vision to which it is always either parallel or perpendicular.

Ratio of Polarized Light

Near the first quarter, contrary to the plane of polarization, the ratio of polarized light shows considerable differences from one point to the other. It varies roughly with the reciprocal of the albedo. On the brightest regions of the whole disk, the ratio does not exceed 48/1000, and on the continents its maximum generally ranges between 65/ and 75/1000. For the seas the variation is generally between 120/ and 160/1000. The greatest polarizations lying between 75/ and 120/1000 are very rare on the Moon. The polarization of the seas varies very irregularly from one point to the other, and this necessitates a good definition of the region under study. The polarization of the continents is more constant and easier to measure. The third column of Table 4 gives

examples of maximum polarizations of a few regions mentioned by order of decreasing albedo (1). These are relative to areas of approximately 1' diameter; depending on the point under consideration the measurements were made either around the first quarter or the last.

No systematic difference is observed between the center and the edges of the crescent when comparing at quadrature the polarization of several regions having the same tint. Near the terminator, however, the polarization goes through a significant increase whose existence was mentioned by Secchi (see French page 3). This effect is very pronounced on the seas where it is detectable from approximately 10 selenocentric degrees from the edge of the shadow. Very near the edge the ratio of polarized light sometimes increases by half its value. The polarization is consequently independent of the angle between the surface of the Moon and the direction of the observer. The ratio of polarized light depends on the angle of incidence of the sunrays only in the neighborhood of the terminator, where this angle is small.

TABLE 4
Polarization of a Few Lunar Regions

Name of Region	Quarter	Max. P	Inversion Angle	Min. P
Very white spot at the location of Furnerius	First	+ 48	.....	- 9.5
Center of the mountain S.S.W. of Proclus	First	+ 65	.....	.....
Continents North of Hipparchus	.....	...	23°35'	.....
Center of the mountain North of Capella	First	+ 75	23 30	- 12.0
Center of Palus Somnii	First	+ 73	.....	- 11.1
Sinus Iridum	Last	+ 120	.....	.....
Mare Nectaris (Southern part)	First	+ 121	.....	.....
Mare Crisium (Southern part)	First	+ 147	23 10	- 12.5
Mare Foecunditatis (West of Messier)	First	+ 140	.....	.....
Mare Imbrium (North-West of Leverrier)	Last	+ 155	22 50	.....
Mare Serenitatis (West of Linné)	.....	...	23 15	- 12.3
Oceanus Procellarum (East of Kepler)	.....	...	22 40	.....
Mare Tranquilitatis (North of Maskelyne)	First	+ 160	23 15	- 12.0
Plato Crater	Last	...	.....	- 11.8
Very dark spot between Eratosthenes and Mösting	Last	+ 170	.....	.....

In passing from first quarter to full Moon, the polarizations of all the regions decrease to the value of the polarization of the Moon as a whole, and the differences between the continents and the seas, so high around the quadratures, becomes almost undetectable. Fig. 8 clearly shows

(1) The values which I found for the general polarization of the Moon and those which are given in this table correspond roughly to a third of the figures given by Landerer and Barabascheff (see French pages 4 and 5). It is difficult to explain such a disagreement. My results confirm, however, those of Lord Rosse who found for the whole of Mare Crisium a maximum of 120/1000.

this phenomenon. The solid line A represents the general polarization of the Moon, the dotted lines D and E are relative to two regions where the polarization is weakest. All these curves approach each other and cut the axis of abscissas at almost the same point. Then the points remain generally on the same curve.

This inversion of the plane of polarization is very curious and I have observed it on several occasions. These facts were observed: Approximately two days before full Moon, when the angle of vision reached 24° at the center, the ratio of polarized light became very small on the whole Moon, whereas the plane of polarization appeared not to have changed. The ratio is on the average smaller at the preceding edge than at the following edge, because there the angle of vision is smaller by 30'. This small effect is in great part hidden by the differences which exist between the seas and the continents.

The polarization first disappears at a zone of approximately 1' radius extending north-west of Tycho, and also at some mountain points of the north-west, then on the continents as a whole, on Sinus Iridum and on a few seas having a reddish tint. Most of the seas and, finally, a region located west of Kepler, also cease to be polarized, but on the continents a beginning of very light polarization of opposite sign is seen, which soon extends to the whole of the disk. The plane of polarization is, as well as can be determined, perpendicular to its previous direction. Only very small differences are observed between the various regions. Near the angle of vision of 11° their polarizations go through very close minima which tend to zero during the Moon eclipses, when exact opposition is approached. Table 4 of (French) page 45 gives a few values of the inversion angle and of the polarization minimum. It is quite remarkable that neither the position of the inversion point nor the amplitude of the minimum depend on the orientation of the lunar surface at the points under observation.

Polarization by Oblique Scattering

Certain vitreous materials, when illuminated at very oblique angles, can polarize light even when they are examined along the direction of the incident rays. This phenomenon was observed by Salet on molten sandstone (1).

I have attempted to determine if the Moon has a similar property. On 19 November 1926, at 2000 hours, or just a few hours after opposition, the polarization was weak on the whole Moon. In order to minimize it I oriented the polarimeter 45° from the plane going through the Sun. Under these conditions certain regions of the far edge of the Moon showed a very weak polarization rising sometimes to 2/1000 and maximally extending to approximately fifteen seconds of arc from the limb. At those points the angle between the area and the visual ray was less than 10°. The plane of polarization seemed to be roughly parallel to the edge.

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(1) Salet, Thesis, 1910, p. 58.

Elliptical Polarization

To date the light from the Moon was believed to be linearly polarized. This belief is confirmed to a first approximation by the fact that the fringes of my polariscope completely disappear when they are oriented at 45° from the plane passing through the Sun. I tried, however, to see if the vibrations coming from certain regions of the lunar ground possess a small ellipticity which to date was undetected. For this purpose I used the refractor of 0.175 m aperture with a diaphragm down to 80 mm in order to minimize as much as possible the influence of the objective lens quality; this influence apparently being zero at the center. The polarimeter, mounted at the eyepiece end, was equipped with the device described on (French) page 26. The quarter-wave plate was capable of 90° rotations so that its axis of slow propagation was either 45° from the right or 45° from the left of the compensating plate axis.

For the measurements I removed the quarter-wave plate from the light beam and I marked the direction of the major axis of the ellipse by the method described on (French) page 18. This operation placed the compensating plate axis at 45° to the left of the plane of polarization, and at 45° to the right of the major axis of the ellipse. If the ellipse is described (to the observer) in the counterclockwise direction when the quarter-wave plate is rotated by 90° after it is placed across the light beam, the plane of polarization of the light which traverses it rotates in the same direction as the plate. A greater position angle is then found when the quarter-wave plate is in its left position as compared to its right position. Let α be the difference between the two readings; the ratio of the axes of the ellipse is equal to $\tan \alpha/2$. The ellipticities found by this method are very small, less than 1/80, and generally in the counterclockwise direction.

On October 24, I tried to determine if these phenomena were caused by the instruments. I rotated the refractor 90° around its axis and repeated the same operations on the same regions. The ellipticities were inverted, which shows that they are due in part to the objective. The lens appears to produce an ellipticity of 6/1000. The Moon is also responsible but to a much lesser extent. On Mare Serenitatis, north-east of Linné, the ratio of the axes of the ellipse appears to be 2.5/1000, while on the mountains north-east of Maurolycus, this ratio seems to be 1.4/1000. The vibration seems to rotate in the counterclockwise direction for the observer. These figures are of the same order of magnitude as the experimental errors.

On the seas, when the polarization reaches 150/1000, the ellipticity is defined to within 1/300 (see French page 19, formula 4). On those continents where the polarization slightly exceeds 50/1000, the error is three times greater. We can therefore consider the light from the Moon as essentially linear. Numerous measurements, repeated for two right angle positions of the objective, would be necessary to show any evidence of ellipticity if it existed at all.

Mercury

Conditions of Observation

The planet Mercury, gravitating around the Sun in an inner orbit as compared to the Earth's, goes through all its phases as the Moon, but its small distance to the Sun seriously limits the conditions under which it can be observed and makes the study of its polarization difficult.

Its elongation does not exceed 27°. If a night is desired for observations free of atmospheric polarization, the two epochs of the year when the ecliptic cuts the horizon at a maximum angle should be chosen. The planet must be observed for either around the spring equinox at sunset, when it is east of the Sun, or around the fall equinox at dawn, when it is west of the Sun.

Unfortunately for those observers residing in the Northern hemisphere, Mercury at these epochs is always near its perihelion and its greatest elongation does not exceed 20°. Its latitude, however, is positive and of 1 or 2°; which somewhat eases the observation.

The ratio of polarized light ceases to be influenced by the polarization of the sky when the Sun is 4° above the horizon. The dusk light is sufficiently weak relative to that of the planet and its almost horizontal plane of polarization is approximately 45° from that of Mercury. In addition, the atmospheric absorption compels the observer to cease measurements whenever the elevation of Mercury drops below 4°. It is therefore necessary to observe Mercury when there is a very clear sky and to operate rapidly. Under the best conditions the available time for observation is only 45 minutes at the greatest elongation and decreases rapidly on either side. The usable period is therefore limited to 20 days during which the angle of vision varies from 60 to 130°, approximately.

Measurements relative to other angles must be made during the day by compensating for the atmospheric polarization. They present serious difficulties. As in the case of the Moon the brightness of the Mercury crescent decreases rapidly when the latter becomes thinner, which prevents its observation for angles of vision greater than 130°. When the angle of vision is smaller than 60°, Mercury subtends an angle of only 5 to 6 seconds. It is near the Sun and in a region where the particles in suspension in the atmosphere scatter a great amount of light. Further, it rarely approaches a brightness equal to that of the sky because of its weak albedo. Therefore, in order to obtain accurate measurements, it is necessary that the atmosphere have an exceptional transparency.

Observations Performed

I took advantage of two favorable periods to observe Mercury by night with the large Meudon refractor.

1. From 16 to 29 May 1922, five observations were made with a consistently good and transparent sky down to a small distance from the horizon.

2. From 7 to 24 April 1924, the sky, while good at the beginning, was spoiled by violent showers followed by clearings which left the sky with a remarkable transparency. By using the refractor at sunset I was able to make use of the short clearings to get a sufficient number of readings.

I made a number of preliminary measurements and carefully determined, as I had for the Moon, the instant when the sky light had weakened enough so as not to influence the results. The

low elevation of Mercury compelled the observer to assume very uncomfortable positions high in the dome. The images were generally extremely agitated and the atmospheric dispersion distorted the planet. In spite of this fact the fringes were easily apparent on the image and the measurements gave values of the polarization to within 2/ to 3/1000. The separate study of the various regions was however impossible. The magnification employed was generally 550, and sometimes 350 when the atmospheric absorption was strong.

I also made a diurnal series of observations from 1 to 20 August 1923, with the 175 mm refractor by compensating the atmospheric polarization with the device described on (French) page 28. During the four final observations Mercury was very pale and the atmospheric polarization changed rapidly compelling the observer to constantly repeat the compensation and measurement became very difficult. The first five results of the series are uncertain and the last four are to be rejected completely.

General Light

The general polarization of Mercury was fairly high and always noticeable along the plane of vision. The ratios of polarized light are given in Table 5. The variations of the ratio of polarized light as a function of the angle of vision are shown by the dashed curve B of Fig. 8, (French) page 42. The observations made during the spring nights of 1922 and 1924 with the large refractor, and those made in the mornings in November 1922 with the small refractor, are indicated by the black triangles. Those of summer 1923 were made during the day with the 175 mm refractor and are indicated by the white triangles.

Around quadrature all the points are located on the same curve contained between the first quarter and last quarter branches of the curve for the Moon. Around the eastern elongations of 1922 and 1924 the polarization of Mercury was greater by only 5/1000 than that of the Moon in its first quarter, and reproduced appreciably its variations. This is a very remarkable result and seems the more surprising when one considers the tremendous difference that exists between the continents and the seas of our satellite.

For angles smaller than 60° the curve for Mercury is not well known. Its general shape is shown by a dotted line, from the first five daytime measurements of 1923, which unfortunately lacked accuracy. The curve seems to coincide with the Moon curve and the polarization appears to invert between 20 and 30°.

Mars

Conditions of Observation

Mars, because it describes an outer orbit as compared to that of the Earth, appears under conditions of illumination much less varied than for the Moon or Mercury. As a matter of fact, it

TABLE 5
Mercury: General Light

Date and Time				V	O	M	E	P	Observations
1922	16	May	2000	86°10' E	81	7	1.6	+ 72.4	
	20		2025	97 23 E	81	3	2.7	+ 72.4	
	23		2015	105 29 E	81	2	1	+ 71.2	
	26		2030	113 34 E	81	2	2	+ 64.4	
	29		2015	121 33 E	81	2	0	+ 60.6	
	1	November	0520	76 45 W	17	2	2	+ 66.6	
	5		0615	60 5 W	17	4	0.8	+ 48.5	
1923	28	July	1400	21 2 E	17	1	...	− 1	
	1	August	1500	31 33 E	15	2	1	+ 2.8	
	4		1100	37 32 E	15	5	1.2	+ 11.9	Poor measurements
	5		1100	39 17 E	15	4	1.3	+ 12.3	
	7		1100	43 7 E	17	4	1.5	+ 23.6	
	10		1100	48 26 E	17	4	3.9	+ 52	
	14		0900	55 14 E	17	3	3.6	+ 57.7	Bright sky, very poor measurements
	17		1400	59 24 E	17	4	3.2	+ 73.5	
	20		1500	63 45 E	17	3	6.8	+ 55.8	
1924	7	April	1930	63 32 E	81	3	0.9	+ 54.8	
	9		1930	72 33 E	81	5	0.7	+ 62.8	
	12		1930	85 28 E	81	6	1.8	+ 69.2	
	16		1900	101 41 E	81	3	1.6	+ 75.2	
	18		1915	109 26 E	81	7	1.4	+ 70.5	
	20		1920	117 2 E	81	5	1.2	+ 71.1	
	21		1930	120 46 E	81	5	0.7	+ 63.3	
	24		1940	131 44 E	81	5	1.5	+ 53.6	

V: Angle of Vision.
O: Free aperture of the instrument in centimeters (numbers smaller than 17.5 correspond to the small refractor; number 60 corresponds to the Cassegrainian telescope; number 81 corresponds to the large refractor).
M: Number of measurements.
P: Mean ratio of polarized light, expressed in thousandths.
E: Mean deviation of the values found for P, from their average.

is known that the phases change little. When Mars is in quadrature the angle of vision goes through a more or less pronounced maximum depending on the distance between the planet and the Sun. It reaches 47° when the planet is still at the perihelion; only 37° when it is at the aphelion. At the opposition the angle of vision goes through a minimum ranging between 0° and 5° depending on the heliocentric latitude of Mars. We can therefore determine only the portion of the curve of polarization between 0° and 47° for this planet.

From the eastern to the western quadrature, Mars twice describes the series of its phases in the reverse direction and can be observed at midnight sufficiently far from the horizon.

Its diameter is then greater than ten seconds, approximately, which allows separate measurement of the polarization of its essential configurations. In addition, because of the appreciable inclination of its equator with respect to the ecliptic plane, the north and south polar regions are alternatingly inclined towards the Earth and their study is facilitated.

Observations Performed

I made seventy-five observations on Mars in three series. The first extends from 11 June to 25 November 1922, the second from 27 April 1924 to 13 March 1925, and the third from 20 June to 6 December 1926.

First Period (1922)

During the first period Mars was at opposition on June 10, at the perihelion on October 13 and at eastern quadrature on October 9. Since the quadrature is close to the perihelion, the angle of vision went up to 46°20', whereas at opposition it went down to 2°2'. The weather remained generally good. All these conditions were very favorable to the determination of the curve of polarization. In addition, the declination of Mars was deeply southern, especially at the date of opposition. Viewed from Paris, Mars went through the meridian at only 15° from the horizon in June, July, August and September, and at 16° then 17° during the first half of October. This fact greatly contributed to image agitation and often precluded the study of details. I therefore decided to regularly measure the polarization of the whole of the planet.

Second Period (1924 – 1925)

During the second period, in 1924, Mars was at western quadrature on April 13, at opposition on August 30, and at eastern quadrature on December 25. Its latitude at opposition was almost maximum so that its angle of vision was down to only 4°58'. At eastern quadrature it did not go beyond 42°29'. The weather, generally good up until July, subsequently became overcast and rainy, which prevented continuous measurements, as in 1922. However, Mars was higher around the end of the observation period, which often contributed to very good images. I took advantage of this situation to study the polarization of the various regions of the planet separately.

Third Period (1926)

During the third period Mars was at western quadrature on 8 July 1926, at opposition on 4 November 1926 and at eastern quadrature on 27 February 1927. At the western quadrature the angle of vision reached 47°22' whereas at opposition the latitude of Mars was very small and went down to 0°21'. I used this period to take some measurements of the polarization of the central regions for comparison with those of 1922, and to systematically search the edges of the disk for

a polarization caused by the obliqueness of the scattered rays similar to the one which certain points of the lunar ground seem to weakly indicate.

Central Regions (1)

Observations of 1922

All the values obtained are shown in Table 6. The points of curve C, Fig. 8, represent the data obtained in 1922. For all the angles of vision smaller than 35° this curve coincides remarkably well with the general curve for the Moon. It departs from it by less than 1.5/1000 at all points. The negative minimum is located, as for the Moon, at 11° but its amplitude is somewhat smaller and is only −10.5/1000. The inversion angle seems a little higher than for our satellite and its most probable value from the curve seems to be 24°15' to within 20'. Conversely, from 35° on, the polarization passes through high fluctuations and its departure reaches 12/1000. These fluctuations are not due only to variations of the angle of vision since the latter remained constant around quadrature and they are not produced by the rotation of the planet because the polarization had very different values corresponding to the same longitudes. They can only be attributed to changes in the physical state of the surface of Mars or of its atmosphere. The results of 1924 will permit an explanation of these fluctuations to be made.

Observations of 1924 – 1925

These observations are shown by the points of Fig. 9. At the beginning of the observation period, around the eastern quadrature of April 1924, the polarization went through irregular fluctuations, and then varied until opposition, as shown by the solid line curve. This curve has the same shape as that of 1922, but its ordinates are smaller except for the small angles of vision. The inversion angle is approximately 26° and is greater than for 1922, and the minimum is more pronounced and reaches −12.5/1000.

After opposition the polarization passed through approximately the same values in the opposite direction and reached 26/1000 on December 6 (values smaller than those for the Moon by 3.5/1000). Two days later it went down to 21/1000 without any apparent cause. Mars showed up with essentially the same regions and since it was soon going into quadrature the angle of vision remained steadily constant. Also, in spite of the excellent quality of the images no fog was visible on the planet, and details close to one-half second from the edge were visible.

(1) The edges of the disk and especially the polar regions are sources of peculiar phenomena and instead of measuring the average polarization of the planet as a whole, I have preferred to study that of a circular area situated at the center and occupying approximately half its area. The measurements were made either by having a fairly small magnification for the refractor so that this area was completely covered by the fringe pattern, or by taking separate measurements with a greater magnification which were later averaged. Since the polarization varied very little from point to point the two methods were equally suitable and gave the same results.

TABLE 6
Mars: Ratio of Polarized Light

Date and Time			V	λ_c	O	C	Regions
1922 11	June	2100	2°22'E	160°	17	− 0.2	
18		2200	7 40 E	113	17	− 9.5	
20		2200	9 21 E	81	81	− 10.3	
22		2100	11 12 E	63	17	− 11.4	
23		2300	11 53 E	91	81	− 9.6	
24		2100	12 47 E	45	17	− 8.8	
28		2200	16 6 E	32	17	− 7.1	
29		2300	16 57 E	30	81	− 7.7	
30		2300	17 28 E	7	17	− 7	T = − 8.2 seas < continents
2	July	2200	19 16 E	349	17	− 6.3	
7		2200	23 3 E	311	17	− 1.5	
8		2300	23 38 E	310	17	− 1.4	
9		2200	23 58 E	286	17	− 0.3	Seas < continents
13		0000	26 51 E	293	81	+ 1.9	
15		2200	28 4 E	232	17	+ 6.2	Seas < continents
16		2000	28 38 E	193	17	+ 6.1	S.cap = + 32 N.cap = + 6.2
18		2100	29 47 E	182	17	+ 10	L and T > C
21		2000	31 26 E	155	17	+ 9.5	S.cap = + 30
28		2200	34 49 E	112	17	+ 16.2	
30		2200	35 39 E	94	17	+ 17	
2	August	2100	36 50 E	59	17	+ 16.9	
8		2000	38 55 E	350	17	+ 19	
9		2000	39 14 E	341	17	+ 19.4	N.cap = + 35
15		2000	40 41 E	275	17	+ 27.2	T > C
16		2000	41 13 E	266	17	+ 30	
20		2100	42 09 E	242	17	+ 26.7	
22		2100	42 30 E	223	17	+ 25.7	
14	September	2000	45 42 E	349	60	+ 29.4	
15		2000	45 45 E	339	60	+ 18.2	
12	October	1800	46 13 E	50	81	+ 21.8	
2	November	1800	45 16 E	72	17	+ 31.8	

TABLE 6 (Continued)

Date and Time	V	λ_c	O	C	Regions
1922 25 November 1800	43°18' E	81°	17	+ 26	
1924 27 April 0400	42 47 W	98	12	+ 25.2	S.cap = + 52
4 May 0400	42 54 W	29	81	+ 22.4	S.cap = + 29
3 June 0300	41 22 W	93	81	+ 17.2	S.cap = + 28
6 0200	40 50 W	50	81	+ 22.1	S.cap = + 26
8 July 0300	32 51 W	121	81	+ 7.7	S.cap = + 15.6 Sirenum = + 11 N = + 6
15 2200	29 11 W	334	17	+ 5.2	S.cap = + 2.7 L = + 4.7 N = + 2.7
19 2300	27 1 W	312	17	0	S.cap > C L > C T < C
26 2300	23 36 W	241	17	− 2.7	S.cap = − 2.7 White Hellas = 0
30 2300	20 23 W	212	17	− 6.8	Maria Sirenum, Cimmerium = − 8.4
					N.hemisphere = − 11.7 L : B = − 7
8 August 2300	13 34 W	131	17	− 12.4	S < C N < C
18 2200	6 28 W	28	17	− 8.8	T > C L : B < C
20 2200	5 38 W	10	17	− 6.4	
22 2300	4 58 W	7	17	− 5.7	
23 September 2100	24 53 E	52	81	+ 0.6	S : B < C N > C T > C
27 October 2100	38 20 E	95	17	+ 17.9	S > C N > C T > L
6 December 1900	42 25 E	40	81	+ 25.7	
8 1800	42 29 E	5	81	+ 20.5	T = L = C Margaritifer sinus = + 20.5
					Hellespontus = + 21.7 Noachis = 19
					Thymiata = 17.4 Aeria, Edom = 19
					N strongly polarized at 0.5"
19 1800	42 21 E	268	81	+ 9.6	2"N = + 15; 1"N : strongly polarized B
					Mars. Foggy especially in the North
					T = + 11 L = + 9
22 1800	42 14 E	222	81	+ 8.2	1.5"S = + 27 : edges < C
					1"N = − 4; 1" to 3.5" = + 4.4
23 1800	42 12 E	206	81	+ 11	2.5"S = + 18.4 2.5"N = + 9.6
					S.S.W. edges = + 15.1 T and L < C
26 1900	42 3 E	204	17	+ 12.2	S > C N < C Seas always pale
29 1800	41 55 E	161	81	+ 11	S = + 16 .8"N = + 13 T = + 8 L = + 11
31 1800	41 48 E	144	81	+ 11.8	.7"S = + 16 N : B = + 16

TABLE 6 (Continued)

Date and Time			V	λ_c	O	C	Regions
1925	5 January	1800	41°28'E	97°	13	+ 12.6	B : 1"S = 0 B : 1"S = 25
	10	1800	41 37 E	157	13	+ 12.4	B : 1"S = 0 T = + 19 L = + 2
	18	1800	40 38 E	338	81	+ 14.5	1"N = + 12 Seas less pale Syrtis Major = + 14.3 Hellas = + 15.8
	22	1800	40 4 E	302	81	+ 13.9	S = + 16 B : 1"N = + 22 T = + 10 L : B = + 5 Yellow Hellas and Yellow Noachis = + 11.8
	23	1700	39 58 E	278	13	+ 13	S : B = + 4 N : B = + 29 T = + 21 L = + 5
	11 February	1700	37 52 E	106	13	+ 15.3	T = + 20 L = + 10
	17	1800	37 1 E	73	81	+ 17.5	L at SW : B = + 4
	13 March	1800	33 37 E	215	81	+ 14.2	N = + 15.5 T > L
1926	20 June	0300	46 43 W	59	81	+ 18	S.cap = + 20 L = + 15
	2 August	0200	46 30 W	10	81	+ 20.5	S.cap = + 22 N = + 18 S = + 17.2
	6	0200	46 9 W	332	81	+ 20.9	S.cap = + 16 N = + 19 light veils
	14 September	0200	37 0 W	321	81	+ 12.5	Syrtis Major and Mare Hadryacum = + 17.6 L = + 29 Hellas = + 9 Aeria-Edom = + 10
	29	2300	29 6 W	130	81	+ 4.8	N : B = + 16 T = + 6 Mare Sirenum = + 7
	13 October	2200	19 10 W	349	81	− 7.7	1"S B = + 7.9 Pol. increases at N
	1 November	2100	2 26 W	167	81	− 1.9	N : B = 0.5
	4	0000	0 40 W	193	81	− 0.5	
	4	1900	0 38 E	111	81	− 1.2	
	14	2000	9 17 E	38	81	− 9	N : B = − 4 T = − 18.8
	15	2100	10 10 E	43	81	− 9.3	.7"T = − 22.6
	6 December	1900	24 41 E	185	81	+ 2	NNE : B = + 13 Mare Chronium = + 29 Mare Cimmerium = + 12.6

V: Angle of vision.
λ_c: Longitude of the center of Mars.
O: Free aperture of the instrument (see Table 5).
C: Regions neighboring the center of Mars.
N and S: Regions neighboring the north and south poles.
L and T: Regions neighboring the limb and the terminator at the equator.
B: White patches.
The numbers mentioned in column C and under "Regions" represent the algebraic value of the ratio of polarized light.

On the 19th the observations were resumed after a few days of bad weather. I found Mars shrouded in a thick fog of yellowish tint, which practically obscured the seas that had been bright during the preceding observations. The polarimeter measured only 9/1000. This thick haze persisted for one month in all the longitudes, whereas the polarization increased slowly and irregularly. On January 18 I saw the details covered again with a lighter fog, whereas the polarization went through a slight increase (1). This clearing remained until the observations were completed and the last two measurements of February 17 and March 13 again gave figures corresponding to those of 1922 and to those of the Moon illuminated in the same way. These anomalies become evident in curve A, Fig. 11, which relates to the disturbed period. It is drawn with the dates of observations as abscissas. The dotted line, curve B, shows the polarization of the Moon for the same angles of vision. The irregularities of the curve of 1922 were also probably caused by fogs much lighter than those of 1924; they would therefore be easily undetected by simple observations.

Observations of 1926

The measurements of 1926 are in rather insufficient number to permit drawing an accurate curve. The solid curve of Fig. 10 shows a weaker polarization than that of 1922 for great angles of vision.

A comparison of these curves with that of the Moon shows that the polarization of the ground of Mars must vary exactly like that of our satellite. The atmosphere of Mars, when very clear, does not appear to exert any influence on the polarization. Sometimes it is shrouded by fogs whose polarization is much weaker than that of the ground, and these fogs seem to exert a significant influence on the great angles of vision. It therefore becomes easy to detect the very light clouds which are directly undetectable.

Regional Study

Seas and Continents

I often compared the seas and continents of Mars that are far from the edges. The differences found among these regions are less pronounced than on the Moon and otherwise seem to be somewhat variable. The polarization of the seas was generally slightly greater than that of the continents. On 8 December 1924, with an angle of vision of 42°, Sinus Meridiani passed through the center of the disk and the polarization reached 17/ to 19/1000 on the continents, 20.5/ to 21.5/1000 on the seas. On 14 December 1926, with an angle of vision of 37°, Syrtis Major and the seas which extend to the south had a polarization of 17.5/1000, whereas continents such as Hellas, Aeria and Edom had a polarization of only 10/1000. Strong polarizations were found on several occasions on Mare Sirenium where, on 8 July 1924, with an angle of 32°51', the polarization

(1) A similar veil was seen in 1909 by Mr. Antoniadi, and the remarkable observations which he made in 1924 with the same instrument (the large Meudon refractor) confirm these aspects.

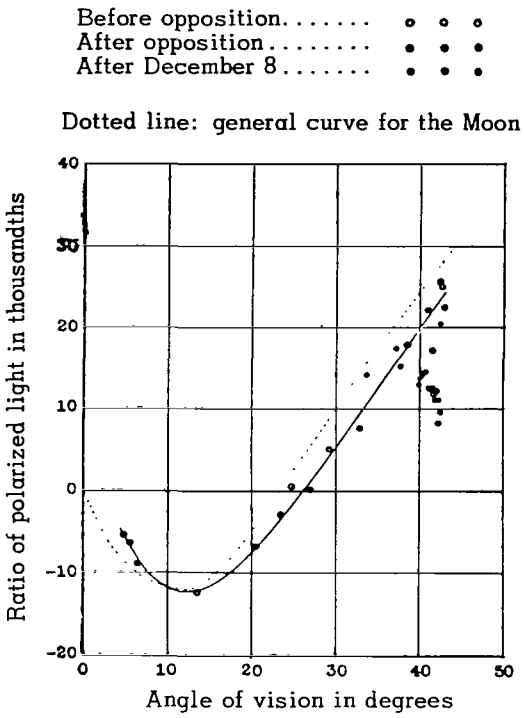

Figure 9. Mars, Central Regions (1924–1925)

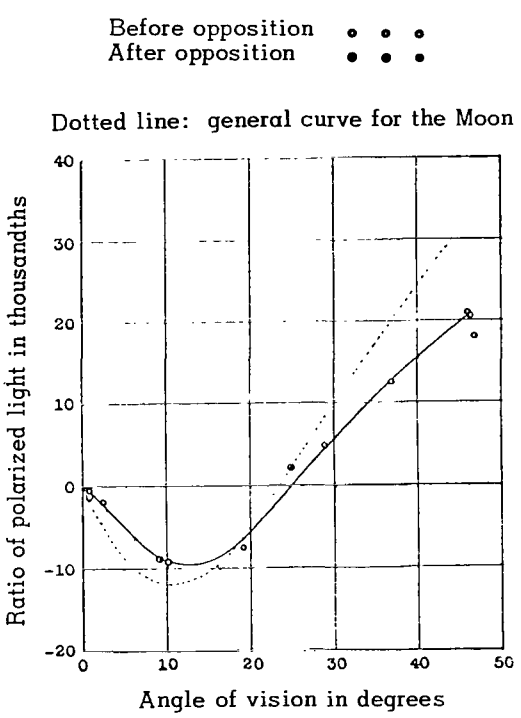

Figure 10. Mars, Central Regions (1926)

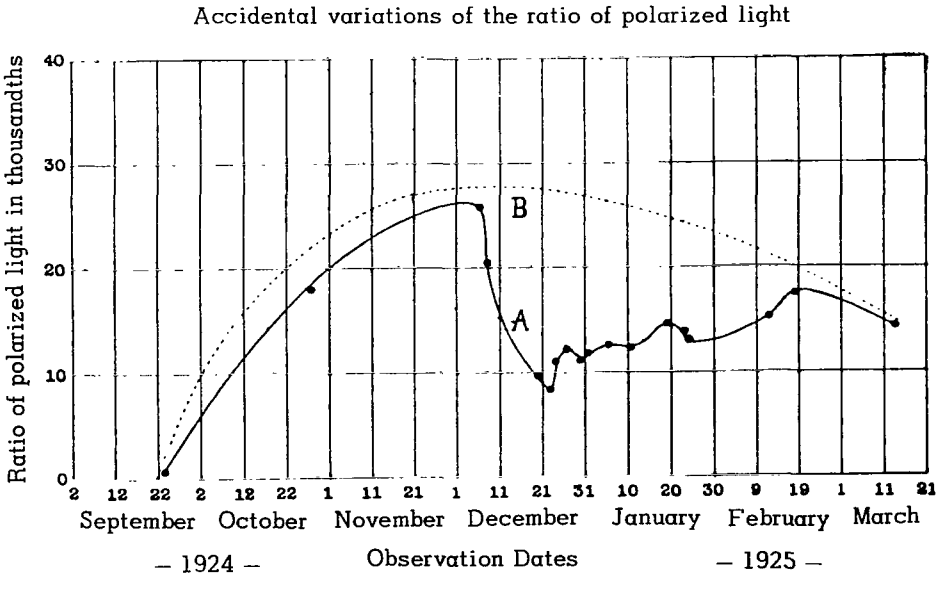
Accidental variations of the ratio of polarized light
Ratio of polarized light in thousandths
40
30
20
10
0
B
A
2 12 22 2 12 22 1 11 21 1 11 21 31 10 20 30 9 19 1 11 21
September October November December January February March
– 1924 –
Observation Dates
– 1925 –

Figure 11. Mars (1924–1925)

was 13/1000, greater by 4/1000 than the average of the central regions. On 29 June 1926 it was 6.7/1000, greater than the average by 2/1000.

For comparison, remember that on the Moon, for the angle of 42°, the difference between the seas and the continents is on the average of 21/1000 and it rises to 5/1000 for the continents. Incidentally, the albedo differences on Mars are much less pronounced than on the Moon.

The Southern Polar Cap

It is difficult to study the polarization of the polar caps of Mars. When they show their greatest extension they come into view under a very oblique angle, whereas at the epochs when the observed pole is highly tilted towards the Earth the Martian summer is close and the white spot loses much of its extension. I have obtained, however, some firm results on the southern cap, especially in July 1922, and from April to July 1924, during the spring of the southern hemisphere. Its polarization was extremely variable. Sometimes it seemed to be the same as for the rest of the planet, and sometimes it was much stronger. In 1922 it was 30/1000 for the angles of vision of 29° and 32°, and in 1924 it appeared to reach 68/1000 around quadratures, whereas in 1926 it remained close to that of the center. From the measurements of 1922 the northern cap seemed to go through identical variations.

Terminator and Limb

The east and west edges of the planet gave results as irregular as those of the polar caps. The terminator and the limb were sometimes more polarized than the center, sometimes less. The difference between the terminator and the center varied between −13/ and +10/1000, and for the limb it was between −10/ and +16/1000. These changes are not due to the rotation of Mars, because I have observed differences of the opposite sign for the same longitudes from the center, and they are not connected with variations of the angle of vision. I shall try to explain these variations later.

Various Clouds

In 1922, and until September 1924, the only observed cloud formations were white patches visible only near the edges, either because the obliqueness of the rays at these points makes them opaque or because the attenuated sun heat allows them to emanate. Those which appeared at the low latitudes were generally pale and diffuse and had a polarization smaller than that of the center. Those which formed at the high latitudes were narrow and bright and occasionally, at the far edge along a band less than half a second wide, had polarizations which were sometimes greater than that of the center, sometimes very much less. Between 8 and 19 December 1924, as mentioned earlier, the planet was completely covered with yellowish veils. These were completely opaque at the north hemisphere and became clearer at the south. The polarization was far from

uniform. In particular, on 22 December, it reached 27/1000 at the southern pole, whereas at the northern pole it was opposite in sign and approximately 4/1000. This difference weakened on the following days and the polarization became zero on the white patches covering the southern pole, and rose to 25/1000 on a white patch visible near the northern pole.

On 18 January, the weather on Mars was much clearer and the polarization much more uniform. White formations were still present near the edges measuring: on January 23, 4/1000 at the southern pole and 29/1000 at the northern pole; on February 17, +4/1000 at the limb in the southern hemisphere.

These observations show that the white patches have a different constitution from that of the yellowish veils. They probably hang at a more elevated level in the atmosphere of Mars since they remained visible during the big atmospheric perturbation.

Polarization by Oblique Scattering

In 1926 I tried to ascertain if certain points on the surface of Mars, when brought near the edges by the rotation of the planet, would show polarization phenomena due to the obliqueness of the rays scattered towards the Earth. The polarization by simple scattering is probably superimposed on these phenomena except during opposition, and must therefore upset their observation. I was able, however, to study them in all weather conditions by orienting the polarimeter at 45° from the direction of the Sun, where the instrument becomes insensitive to simple scattering. The points near the edge and situated roughly at 45° from this direction can therefore be studied. Below are a few results obtained in this way.

On November 1, at 2100, a fairly white region appeared at the following south edge, approximately on Thyle II. Its polarization was parallel to the edge and equal to 7/1000, and the scattered rays formed an angle of approximately 20° with the surface. There was no noticeable polarization on the three other quadrants.

On November 14, a white patch on Aonius Sinus appeared at the following south edge. The polarization was along a tangent to the edge and was equal to 5/1000. The average angle of scattered rays was 20° approximately. There was a slight polarization along the tangent at the opposite edge.

On November 15, at 2100, the white patch on Aonius Sinus at the following southern edge had a polarization parallel to the edge, equal to 6/1000, and with an average angle of 17°.

At the following north edge, on Arcadia and near Ceraunius, the polarization was parallel to the edge and equal to 9/1000, and the average angle was 13°.

On December 6, at 1900, the angle of vision was 24°41'. The polarization was weak around the center. The seas, around Mare Chronium, had a very strong east-west polarization of 29/1000,

rapidly increasing towards the edges, for an angle of approximately 50°. This polarization seems to be due in part to the oblique scattering of light.

In summation, I observed a polarization which seemed to be due to the scattering of light by oblique surfaces of white patches appearing at the eastern edge, once on Thyle II and twice on Aonius Sinus. The same is true of Arcadia, however, no white patch was observed here, probably because of the brightness of the neighboring regions. A similar phenomenon must have occurred on the dark patches situated north of Mare Chronium. I shall describe in Chapter VI some phenomena observed on Earth which provide an explanation for these observations.

Venus

Conditions of Observation

Because it describes an inner orbit to that of the Earth, the planet Venus goes through very different phases and its angle of vision takes all the values between 0 and 180°. On the other hand, Venus lends itself much better than Mercury to polarization measurements because of its greater distance from the Sun and because of its much higher albedo. Since its maximum elongations are about 46°, it can be studied by night when the conditions are favorable, and during a great part of its phases. The usable period goes from 24 to 156° if the observations are made, as for Mercury, in the evening around the autumnal equinox.

During periods of clear sky, Venus always has a brightness greater than that of the sky. Its ratio of polarized light can be measured in all weather conditions in daytime with an error less than 3/1000, according to the formula of (French) page 29. Around its superior conjunction its apparent diameter does not go below 12", which permits the use of small instruments so that it becomes simple to protect the objective against sunrays. Around its inferior conjunction the difficulties caused by its crescent becoming thinner and thinner are compensated in part by the considerable increase in its brightness which is the opposite of what occurs for the Moon and Mercury. These very favorable conditions permit a more complete determination of the polarization curve for Venus than for the Moon and the other planets. The observation of the separate regions is also greatly facilitated in the case of Venus, as compared to that of Mercury, because of its greater apparent diameter which reaches 21" during its greatest elongation, and because of the possibility of night time observation, far from the horizon, where the images are generally less agitated.

Observations Performed

I made 111 observations on Venus, between 13 May 1922 and 6 July 1924, during which period the planet described two and a half times its phase series. Around the greatest elongation the measurements were almost always made during the night and preferably with the large Meudon refractor. On the other hand, when Venus was close to the Sun, I observed during the day with the

175 mm refractor equipped with the device built to compensate for the atmospheric polarization (see description, French page 27).

The first measurements were made somewhat irregularly except for some continuous observations made in August 1922 for the purpose of detecting rapid changes of the polarization. From April to September 1927 I studied the planet more continuously, especially in August. The sky, very blue during the end of this period, permitted me to continue the observations to around superior conjunction.

On September 9, Venus was only 1°20' from the Sun. The measurements were then made with the 160 mm finder from the large refractor, whose objective was in the shadow of a screen mounted at the end of a 16 m long tube. On 31 March 1924, I started another series of regular observations with the large refractor in the evening. The angle of vision increased and reached 76°48'. The observations were facilitated by the frequency of beautiful evenings. The images were fairly calm and permitted the study of separate points of the Venus crescent, and in particular the terminator, the limb and the horns.

On June 16, the angle of vision reached 148°46' and nighttime observations became impossible. However, I could then continue the regional study during the day with the 175 mm refractor, thanks to very clear weather, and I could take measurements up to inferior conjunction where /64
Venus was only 3-1/2° from the Sun.

General Light

Plane of Polarization

The average plane of polarization of Venus was always found to be either parallel or normal to the plane going through the Sun, with an approximation equal to that of the measurements.

Ratio of Polarized Light

The figures obtained for the ratio of general polarized light for Venus are listed in Table 7. /66
The solid curve of Fig. 12, represents variations of the ratio of polarized light as a function of the /68
angle of vision. The angle went through the whole series of values ranging from 2° to 176° approximately, during each interval between two successive conjunctions. The observations mentioned are relative to three of these intervals and the polarizations for each of them are represented by points of different shapes. The white points are the measurements corresponding to the day, the black ones to the night. In spite of the variety of instruments and methods by which they were obtained, the six kinds of points overlap in many places and depart little from the same curve, except for some accidental irregularities. This very remarkable fact shows that the apparent surface of Venus did not change during my observations and leads to the supposition that its atmosphere is not acted on by frequent perturbations, as in the case of Mars.

TABLE 7
Venus: Ratio of Polarized Light

Date and Time			V	O	M	E	P	Observations
1922	13 May	2020	33°54' E	81	3	0.8	− 11.6	
	15	2020	34 42 E	81	2	1.4	− 13.3	
	20	2020	36 47 E	81	2	0.1	− 15.4	
	23	2010	38 0 E	81	1	...	− 13.6	
	26	2015	39 34 E	81	1	...	− 15.9	
	29	1955	40 28 E	81	3	0.6	− 13.1	
	20 June	2030	49 50 E	81	5	0.7	− 12.4	
	23	2030	51 9 E	81	4	0.5	− 13.7	
	29	2030	53 45 E	81	4	0.7	− 12.2	
	17 July	1600	61 27 E	13	1	...	− 8.6	Instrument not adjusted
	28	2020	66 35 E	17	6	0.3	− 14.3	
	30	2030	67 19 E	17	3	0.3	− 13.7	
	1 August	2005	68 24 E	17	4	0.2	− 19.2	
	2	2000	68 51 E	17	3	0.3	− 16.2	
	4	2015	69 47 E	17	1	...	− 19.6	
	8	2005	71 36 E	17	3	0.5	− 23.8	Violent wind
	9	1955	72 07 E	17	3	...	− 21.4	
	10	2000	72 33 E	17	4	0.3	− 17.9	
	11	2100	73 4 E	17	4	0.4	− 19.8	
	12	1945	73 31 E	17	6	1.0	− 22.5	
	15	1945	74 58 E	17	3	0.2	− 21.4	
	16	1945	75 25 E	17	3	0.5	− 21.2	
	18	2045	76 24 E	17	3	0.2	− 20.4	
	20	2040	77 22 E	17	2	0.1	− 22.2	
	22	2030	78 21 E	17	1	...	− 21	
	14 September	2100	90 56 E	60	3	4	− 29.4	
	18	1835	93 24 E	60	3	1.1	− 26.4	
	29	1820	100 30 E	60	2	0.6	− 31.1	
	12 October	1750	111 6 E	81	2	1.8	− 29.7	
	7 December	0735	154 21 W	17	3	0.6	+ 13.6	
	9	0740	150 30 W	17	3	0.5	+ 11.9	
	13	0650	143 12 W	17	4	0.1	− 10.3	
	15	0715	139 50 W	17	6	1.7	− 11.6	
	22	0700	129 17 W	17	7	1.2	− 25	
1923	11 January	0645	107 19 W	12	5	1.4	− 31.2	
	23	0730	98 14 W	17	1	...	− 22.8	Bright day
	5 April	0720	61 30 W	12	2	0.7	− 15.8	
	9	0900	59 51 W	12	1	...	− 17.5	
	10	0900	59 39 W	12	1	...	− 17.5	
	11	0900	59 3 W	11	5	0.5	− 15.2	Insufficient compensation
	25	0930	53 31 W	12	3	0.3	− 16.1	
	2 May	1000	50 48 W	12	1	...	14.2	
	16	1000	45 24 W	12	3	0.7	− 15	

TABLE 7 (Continued)

Date and Time			V	O	M	E	P	Observations
25		1115	42 45 W	12	2	1.4	− 15.1	
19	June	1000	32 17 W	17	3	0.3	− 12.6	
5	July	1000	26 1 W	13	4	0.5	− 2.4	
12		1000	23 19 W	13	2	...	+ 0.5	
19		1000	20 35 W	15	3	1.4	+ 8.4	
21		1000	19 47 W	17	2	0.6	+ 9.8	
26		1600	17 51 W	17	5	0.6	+ 13.9	
1	August	1000	15 30 W	13	3	1.4	+ 15	
3		1000	14 43 W	15	3	0.6	+ 15.2	
5		1100	13 56 W	15	2	0.5	+ 15.6	
8		1000	12 46 W	17	4	1.6	+ 13.7	
11		1400	11 32 W	17	2	0.6	+ 14.7	
14		1000	10 16 W	17	3	0.5	+ 9	
16		1000	9 44 W	17	3	1.1	+ 6.2	
19		1500	8 33 W	17	4	0.7	+ 2.7	
20		1400	8 12 W	16	6	0.2	+ 1	
21		1000	7 53 W	15	3	...	− 0.3	
22		1000	7 32 W	15	4	...	− 0.3	
23		1000	7 9 W	15	3	0.3	− 2.2	
25		1000	6 24 W	15	4	0.3	− 1.1	
26		1000	5 53 W	13	7	0.4	− 1.5	
27		1000	5 30 W	15	3	0.2	− 1.8	
28		1000	5 18 W	12	3	0.3	− 1.9	
29		1000	4 56 W	11	4	0.5	− 1.1	
9	September	1430	1 58	16	8	...	+ 0.7	
27		1400	6 46 E	13	5	0.5	− 1.2	
30		1300	7 7 E	13	3	0.1	+ 0.6	
1924 7	January	1430	41 21 E	13	3	0.9	− 13.2	
12		1130	43 5 E	15	3	0.4	− 12.7	
24		1300	47 26 E	12	4	0.9	− 14.1	
2	February	1200	50 50 E	12	3	0.9	− 17.7	
14		1400	55 35 E	12	9	2.3	− 19	Difficult measurements, cloudy
2	March	1000	62 40 E	12	6	0.4	− 17.4	
8		1200	65 22 E	12	5	0.8	− 18.1	
15		1200	68 39 E	12	4	1.9	− 18.8	
31		2000	76 48 E	81	3	0.4	− 20.1	
5	April	1930	79 29 E	81	4	0.3	− 20.7	
6		2030	80 3 E	81	4	0.4	− 21.1	
7		2000	80 35 E	81	5	0.5	− 19.6	
9		2000	81 46 E	81	2	0	− 23.4	
12		2000	83 29 E	81	4	0.6	− 24.5	
18		2000	87 7 E	81	2	0.4	− 23.8	
19		2010	87 55 E	81	2	0.1	− 25.2	
20		2000	88 22 E	81	1	...	− 21.9	

TABLE 7 (Continued)

Date and Time		V	O	M	E	P	Observations
21	2000	88 59 E	81	1	...	- 24.5	
24	2000	90 58 E	81	1	...	- 25.3	
3 May	2100	96 51 E	81	3	0.6	- 25.3	
5	2000	97 20 E	81	3	0.5	- 26.8	
9	2100	102 5 E	81	3	0.7	- 28.5	
17	2100	109 9 E	16	4	0.6	- 28.9	
26	2100	118 29 E	81	2	0	- 30.3	
2 June	2100	127 16 E	81	3	0.3	- 25.9	
5	2030	131 20 E	81	3	0.4	- 27.2	
7	1200	136 49 E	17	2	0.2	- 28.2	
9	2030	137 23 E	81	5	1	- 20.7	
12	1200	141 45 E	17	9	1.4	- 9.5	
14	1400	145 26 E	17	2	0.7	- 2	
15	2030	147 40 E	81	6	0.8	- 0.5	
16	1100	148 46 E	17	6	1.5	+ 3	
16	2040	149 30 E	81	7	1.2	+ 6.5	
19	1100	154 29 E	13	7	2.1	+ 19	
21	1030	158 25 E	17	2	0.1	+ 18.2	
23	1300	162 40 E	17	7	3	+ 17.8	
24	1200	164 35 E	13	8	0.9	+ 16.1	
25	1400	166 42 E	17	6	1.4	+ 12.1	
29	1100	173 44 E	13	7	0.5	+ 1	
30	1200	175 E	13	4	1.1	- 5.2	
1 July	1200	175 18	13	4	1.7	- 5.2	

The symbols are the same as for Table 5.

The measurements of September 29, 1923 were made with the 160 millimeter finder of the large refractor.

The measurements of May 17, 1924 were made with the 160 millimeter finder of the Meudon 1 m refractor.

The polarization of Venus is very puzzling and does not resemble the polarizations of the Moon, Mercury or Mars. The ratio of polarized light changes sign four times at the following angles of vision: 7, 24, 147 and 173°. It is positive between 7 and 24°, and negative between 24 and 147°. Therefore, when Venus and the Moon appear in the same phases their lights are generally polarized along mutually perpendicular planes.

Regional Studies

Full Phase

On 1 August 1923, I started to study the various regions of Venus separately. The figures obtained are listed in Table 8. At that time the angle of vision was 15°30'. The planet approaching its

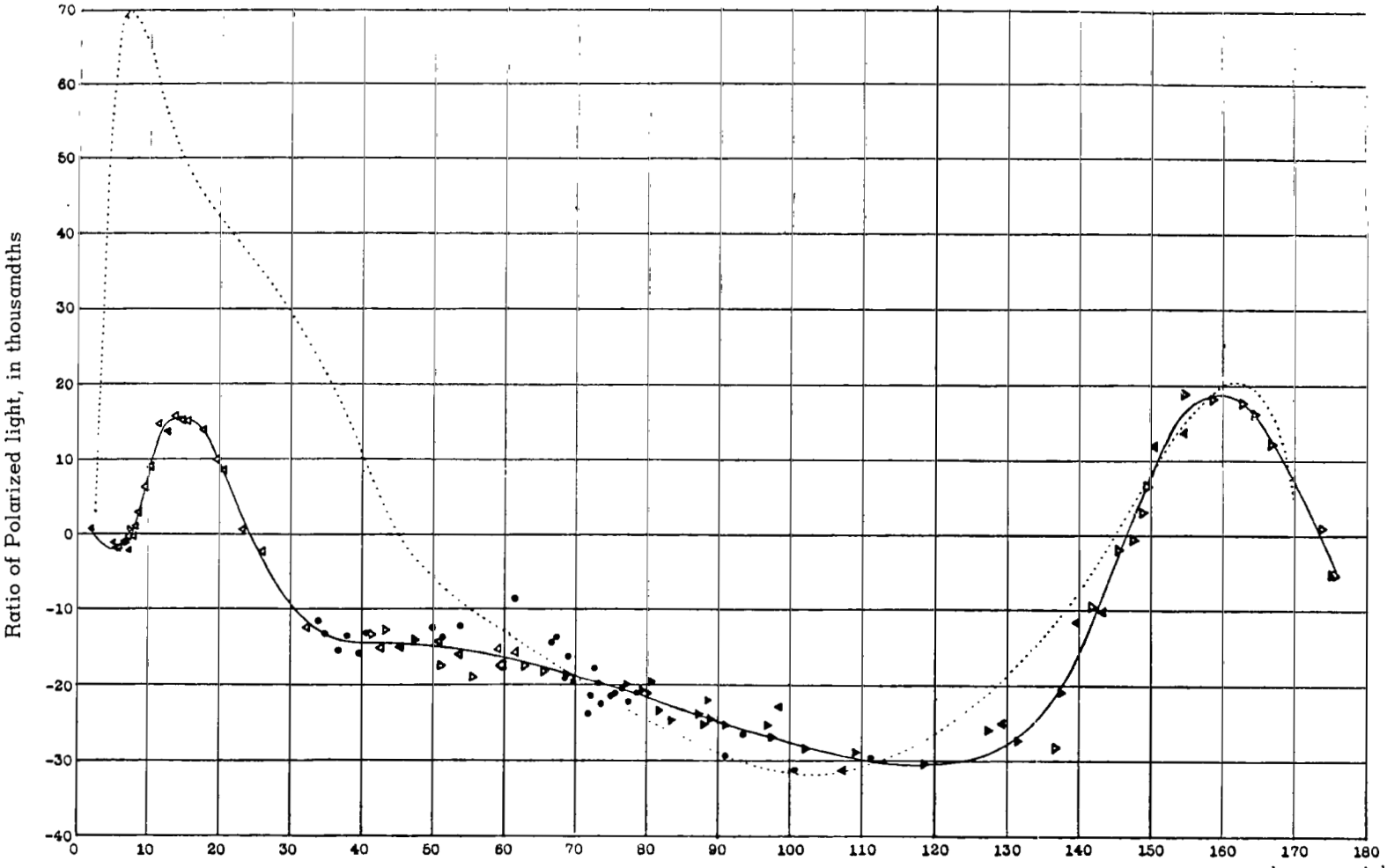

Figure 12. Venus, General Polarization

TABLE 8

Venus: Regional Study

Date and Time			V	X	O	Ratio of Polarized Light: Center	Limb	Terminator	North Horn	South Horn	Plane of Polarization: Center	North Horn	South Horn	Observations
1922	20	June	2100	49°50' E	....	81	− 12.5	− 12.9	− 17	.....	.....	.....	.....	.....	
	11	August	2100	73 4 E	....	17	− 20.6	.....	<	.....	.....	.....	.....	.....	
1923	1	August	1000	15 30 W	....	13	+ 15.5	<	<	.....	.....	.....	.....	.....	
	5		1100	13 56 W	....	15	+ 17.2	<	<	.....	.....	.....	.....	.....	Excellent images, clear sky
	11		1400	11 32 W	....	17	+ 15.9	>	>	.....	.....	.....	.....	.....	
	14		1000	10 16 W	....	17	+ 9.6	>	<	.....	.....	.....	.....	.....	
	19		1500	8 33 W	....	17	+ 2.6	<	>	.....	.....	.....	.....	.....	Cloudy sky
	21		1000	7 53 W	....	15	0	0	0	0	0	.....	.....	.....	
	25		1000	6 24 W	....	15	− 1.6	<	>	N < C	S < C	.....	.....	.....	Unsteady images
	26		1000	5 50 W	....	13	− 1.7	<	>	.....	.....	.....	.....	.....	
	9	September	1400	1 58	....	16*	+ 0.7	=	=	N = C	S = C	.....	.....	.....	Clear sky at times
1924	5	April	2000	79 29 E	....	81	− 20.7	=	=	N = C	S + C	.....	.....	.....	
	20		2000	88 22 E	....	81	− 21.9	.....	.....	− 35.2	− 29	.....	.....	.....	
	21		2000	88 59 E	....	81	− 26.5	.....	.....	31	.....	.....	.....	.....	
	24		2000	90 58 E	82°.1	81	− 25.3	.....	.....	.....	.....	171	165.1	175	
	3	May	2100	96 51 E	....	81	− 25.3	.....	.....	33	33	.....	.....	.....	
	5		2000	97 20 E	86°.1	81	− 26.8	.....	.....	.....	.....	172.2	167.7	179	
	9		2100	102 5 E	....	81	− 28.5	.....	.....	30.2	39.2	.....	.....	.....	
	26		2100	118 29 E	93°	81	− 30.3	− 28	− 42	33.2	43.3	183	177.5	186.7	
	5	June	2100	131 20 E	94°.4	81	− 27.2	25.1	31.3	27.8	28.3	186.7	181.5	191	Very steady images
	9		2100	137 23 E	95°.1	81	− 20.9	.....	.....	− 17.8	− 18	187	182.3	192.3	Steady images
	15		2100	145 26 E	....	81	− 0.5	.....	10	+ 0.5	.....	.....	.....	.....	
	23		1400	162 40 E	....	17	− 16.4	.....	.....	.....	.....	.....	.....	.....	Clear sky, sinuous crescent
	24		1200	164 35 E	....	13	− 18.2	.....	.....	10	10	.....	.....	.....	

V: Angle of vision. X: Position angle of the plane of vision. O: Free aperture of the instrument (see Table 5).

Measurements relative to the horns are made at a distance from the peaks equal to 1/4 the diameter for the ratio of polarized light, and at a distance of 1/7 the diameter for the plane of polarization. For the period going to full phase, measurements are made of the regions neighboring the north and the south edges.

The measurements of September 9, 1924, are made with the 160 millimeter finder of the large telescope. The symbols > and < mean that the ratio of polarized light is algebraically greater or smaller than that of the center.

superior conjunction had, as seen through the 175 mm refractor, the shape of a uniformly bright disk with no detail showing, although the images were often good. In spite of this the polarization was generally not completely uniform and the differences changed within a few days. These changes are probably due to a rotation movement of the planet, but the observations are not enough to prove this point.

At the time of the inversion of 21 August 1923, the polarization was zero on the whole disk. The same was true of September 9, very near to the superior conjunction, but here the brightness of the sky in the direction of Venus made the measurements less accurate.

I resumed the regional studies on the night of 5 April 1924, with the large refractor. At that time the angle of vision was 79°29' and the polarization was very uniform on the whole planet.

Horns, Plane of Polarization

On April 21, with an angle of 89°, the situation had changed. The plane of polarization, normal to the plane going through the Sun, i.e., parallel to the horns, in the widest part of the crescent, rotated toward the peaks in the opposite direction to the corresponding radius vector of the planet. The deflection seemed maximum at a distance from the peaks slightly less than a quarter of the radius of Venus and closer to the limb than to the terminator. It kept an approximately constant value of 5° until about June 9 (V = 137°23'). From that date on I could not continue the azimuthal measurements because the polarization was too weak and because of the daylight. Nothing similar to this occurs with the Moon, whose plane of polarization is constant to within less than half a degree.

Horns, Ratio of Polarized Light

This deviation on the horns was accompanied by changes of the ratio of polarized light. On April 20, the polarization had become much more negative at the horns than at the center and the same was true until June 5. Its algebraic value decreased regularly starting at a distance from the center which was approximately equal to one quarter the radius of Venus, to reach a minimum near the peaks. This difference, measured a half radius away from the peaks, was generally not the same at the north and at the south and seemed to oscillate irregularly between 2/ and 8/ 1000. At the north peak it reached -13/1000. On June 5, the horns were almost equal at their centers, and on June 9, the difference had changed sign.

Limb and Terminator

During that period the polarization was algebraically less at the terminator than at the limb, and it slowly varied near the limb. At the terminator the drop was more pronounced and was sometimes considerable. On May 26 the difference between the two edges of the crescent reached

14/1000. The polarization reversed first at the limb, just before June 15, then at the terminator some time later. For several days the two edges of the crescent were oppositely polarized, and on June 23 in particular this fact showed up in a very perplexing way. The polariscope was oriented so that the fringes traversed the mid-crescent perpendicularly, and the atmospheric polarization had been cancelled with the pile of photographic plates. I placed the two plates of the polarimeter perpendicular to the axis of the refractor and observed the fringes disappear and the crescent become sinuous. Its width did not then exceed 1.5" and its aspect was that of Fig. 13. This phenomenon was due to the presence of two sets of complementary fringes which alternately reinforced the limb and the terminator. This aspect persisted on the next day, then disappeared, probably because the width of the crescent became less than the resolving power of the refractor. In spite of its thinness which probably increased much more until inferior conjunction, the crescent remained quite visible in the very bright sky. Its brightness must have therefore increased, which is the opposite of what occurs for the Moon.

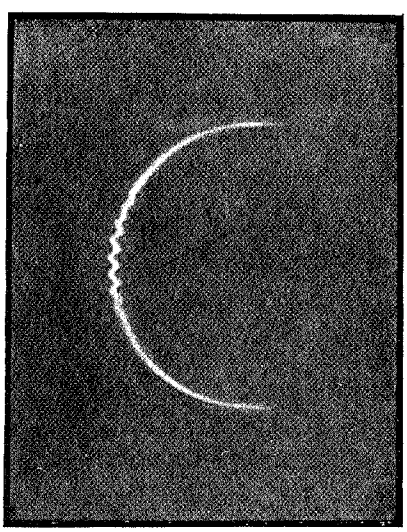

Figure 13. Appearance of Venus, as seen through the Polarimeter, on June 23 and 24, 1924

Jupiter

Conditions of Observation

Because of its great distance to the Sun, Jupiter comes into view almost completely. Its phases are known to be limited to a thin shadow along either one of its two edges. The angle of vision reaches its maximum at quadratures where it never exceeds 11°52'. At oppositions this angle always falls below 0°17' because of the weak inclination of the orbit. We can therefore know only a very small portion of the polarization curve, described twice in opposite directions from western quadrature to eastern quadrature.

Jupiter rotates around an axis almost normal to the ecliptic plane, therefore its poles come into view very tilted. The observations are however facilitated by its constantly high apparent diameter (37" at the quadratures) and by its great brightness which is equal to that of Mars at the perihelic oppositions. A 175 mm aperture refractor is sufficient to study its essential details separately.

I started the measurements in 1922. From that date on the declination remained deeply southern. Its maximum elevation above the horizon at Meudon was 37° at the 1922 opposition, and went down to 19° in 1924 and 1925 to reach 26° again in 1926. The southern pole of Jupiter remained slightly tilted towards the Earth during the whole series of observations. The latitude of the center, maximum at the beginning, changed subsequently from -3° to 0°.

Central Regions

The first measurements showed that around the center of Jupiter there was a very uniform polarization which seemed to vary regularly with the direction of the incident rays, as in the case of the planets described earlier. Around the poles, however, the polarization seemed to behave very differently. This is why, instead of measuring the general light of Jupiter, I chose to study the average polarization of a patch occupying the center of the disk and extending approximately half a polar diameter.

I started the measurements on 15 May 1922, long after opposition. The angle of vision was already 7°30'. The measurements gave for the center a plane of polarization approximately perpendicular to the plane going through the Sun. The ratios of polarized light found are listed in Table 9. The negative polarization, close to zero at the beginning, rapidly reached 6/1000 to remain almost constant later during the month of June.

In 1923 the measurements were more frequent. They are represented by the points of Fig. 15. The positive weak polarizations of the beginning went through zero approximately 25 days after opposition, to reach -5.5/1000 at quadrature. In 1924, as shown on Fig. 16, the polarization, negative at the beginning, became exactly nil at opposition for about 15 days, and went down to -6/1000 just before quadrature.

In 1925 the changes seem to lie between those of 1923 and 1924, but the measurements are too few to permit the construction of a curve. The points for 1926 give curve 17, which is similar to that of 1924, but shows less curvature.

All these curves were drawn without considering the longitude of the center of Jupiter corresponding to each observation. They show no greater discrepancies than the probable errors of measurement. Along the equatorial zone of Jupiter, however, all the points of its apparent surface have the same physical state. This state does not change appreciably between two observations but it does change slowly each year along all the longitudes. Visual observations and the photographic method reveal a similar property. In fact it is known that the planet is surrounded by

TABLE 9
Jupiter: Ratio of Polarized Light for the Equatorial Regions

Date and Time			V	O	Central Regions	North Band	Equat. Zone	South Band	West Rim	East Rim
1922	15 May	2200	7°30'E	81	− 1.4	....	....	....	....	....
	1 June	2200	9 28 E	81	− 4.4	....	....	....	....	....
	11	2100	10 8 E	17	− 6.2	....	....	....	....	....
	18	2100	10 30 E	17	− 4	....	....	....	....	....
	23	2300	10 35 E	81	− 5.3	− 4.8	− 5.5	− 5.5	....	....
	28 July	2100	9 55 E	17	− 2.2	....	....	....	....	....
	10 August	2100	9 7 E	17	− 0.6	....	....	....	....	....
1923	23 April	2000	2 26 W	16	+ 1.2	....	....	....	....	....
	1 May	2200	0 53 W	16	+ 0.4	....	+ 0.7	....	....	....
	14	2100	1 49 E	17	+ 1	− 0.6	+ 1.6	− 0.6	....	....
	30	2100	4 52 E	17	− 0.6	− 0.5	− 0.8	0	....	....
	1 June	2200	5 13 E	17	− 0.5	+ 0.5	− 0.8	+ 0.5	....	....
	11	2100	6 52 E	17	− 1.5	− 1.9	....	− 1.1	....	....
	17	2100	7 43 E	17	− 2.0	− 1.3	− 2.0	....	....	....
	24	2100	8 41 E	17	− 2.7	− 1.5	− 2.5	− 1.5	....	....
	3 July	2100	9 31 E	17	− 3.5	− 5.6	− 2.2	− 4	....	....
	11	2100	10 7 E	17	− 5.1	− 7.4	− 3.5	− 6.2	....	....
	20	2000	10 36 E	17	− 4.4	....	− 4.4	....	....	....
	5 August	2000	10 50 E	15	− 5.4	....	....	....	....	....
1924	4 May	0200	6 19 W	81	− 1.3	− 0.9	− 1.2	− 1.8	....	....
	10	2200	5 17 W	81	− 1.3	....	− 1.3	....	....	....
	26	2300	2 16 W	81	+ 0.2	0	0	+ 0.5	....	....
	2 June	2300	0 39 W	81	0	....	0	0	....	....
	10	0100	0 50 E	81	0	....	0	....	+ 1.6	+ 1.6
	15	2300	2 9 E	81	− 1	− 0.6	− 1.2	....	+ 2.8	....
	16	2200	2 21 E	81	− 0.8	....	− 0.8	....	+ 2.3	+ 1.2
	25	2300	4 1 E	81	− 1	− 1	− 1	− 0.6	+ 2.7	+ 1.1
	7 July	2300	6 1 E	81	− 0.3	....	− 0.3	....	+ 2.1	+ 0.8
	15	2200	7 25 E	17	− 2.7	....	....	....	+ 0.5	+ 0.5
	19	2100	7 59 E	17	− 5	....	....	....	− 0.2	+ 0.5
	26	2100	8 44 E	17	− 4.3	....	....	....	< 0	< 0
	30	2300	9 16 E	17	− 4.7	− 3.8	− 5.2	− 4.8	< 0	< 0
	6 August	2100	9 58 E	17	− 6	....	....	....	− 2	− 4.2
1925	16 June	0100	4 46 W	81	− 2	− 2.2	− 2.3	− 1.2	+ 1.2	+ 2.5
	30	2300	2 0 W	81	+ 0.2	+ 0.5	0	0	+ 1.3	+ 2.5
	8 August	2100	5 53 E	13	− 2	− 2.5	− 1.8	2.5	+ 0.5	− 0.3
1926	21 May	0200	11 30 W	81	− 6.3	....	− 6.3	....	− 4.1	− 4.9
	20 June	0000	9 56 W	81	− 5.6	....	....	....	− 2.0	− 3.2
	2 August	0100	3 0 W	81	+ 0.5	....	....	....	....	....
	6	0000	2 10 W	81	+ 1.8	....	....	....	+ 2.5	+ 1.8
	27	2200	2 38 E	17	0	....	....	....	0	+ 0
	8 September	2100	5 3 E	81	− 1.2	....	....	....	+ 0.5	− 1.1

TABLE 9 (Continued)

Date and Time	V	O	Central Regions	North Band	Equat. Zone	South Band	West Rim	East Rim
13 2200	6 1 E	81	- 1.6	- 1.2	- 2.1	....	+ 2.8	0
29 2200	8 33 E	81	- 3.8	....	- 4	- 2.9	0	- 1.6
1 November 2100	11 16 E	81	- 5.5	- 7.7	- 4.9	....	- 1.3	- 2.8
6 December 1800	10 30 E	81	- 5.5	- 6.7	- 5.5	....	0	- 4.0

V: Angle of vision.
O: Free aperture of the instrument in centimeters (see Table 5).
The polarization of the Eastern and Western rims was measured at a distance of 0.06 equatorial diameters from the limb.
Extension of the polarization of the rims, as fractions of the polar diameter:
15 June 1924 : 0.20 West
9 June 1925 : 0.10 West; 0.11 East
30 June 1925 : 0.21 West; 0.25 East
13 Sept. 1926 : 0.25 West and East

bright and dark belts, parallel to its equator, which appear generally at the same time along their whole length and whose different parts generally go through roughly simultaneous changes. The polarization curves of Jupiter are not like those of the other planets; the ordinates have the same sign as for the Moon, but are much weaker and the curvature is reversed.

Belts

I have frequently compared the polarization of the bright and dark belts around the central meridian, and especially the clear equatorial zone, the two strongly dark tropical belts and the adjacent clear zones. As shown in Table 9 their polarizations often seem identical. Even when the fringe aspect seemed slightly modified on one of them, the measurements gave differences generally less than the observational errors. To mention a few exceptions: On 3 May 1923 the equator had a polarization of +1.6/1000, greater than that of the adjacent zones by 2/1000; on 24 May 1923 the polarization was -2.5/1000 at the equator as against -0.5 on the belts. The greatest difference was registered on July 11 when I found -7.6 for the north belt, -6.2 for the south belt and -3.7 for the equatorial belt.

East and West Rims

In 1924 I consistently measured the polarization of the regions situated along the rim near the equator. The plane of polarization there, as in the center, was sometimes parallel, and sometimes normal to the plane going through the Sun. The ratio of polarized light was always algebraically higher, and at the center, as we have seen, very uniform. At a distance from the rims,

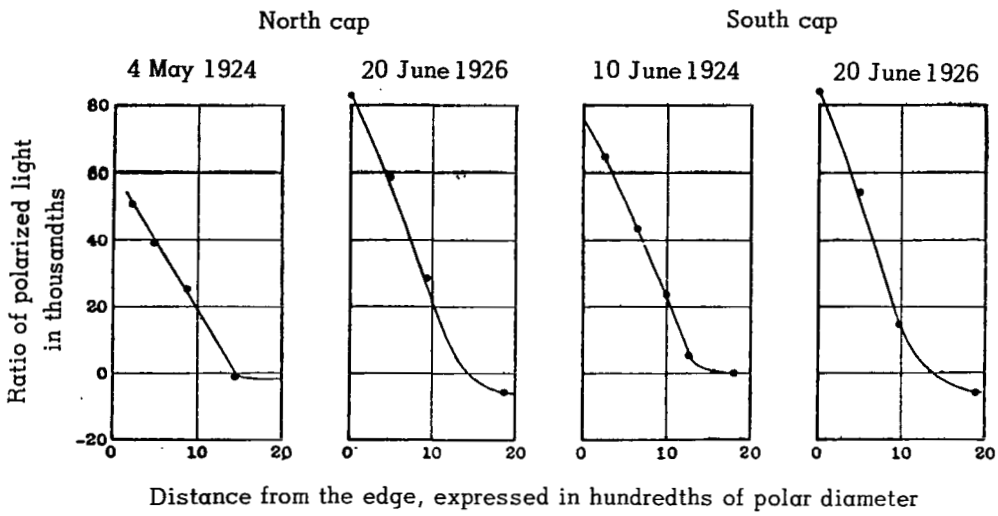

Figure 14. Polar Caps of Jupiter

Central regions of the planets Jupiter and Saturn—Ratio of polarized light

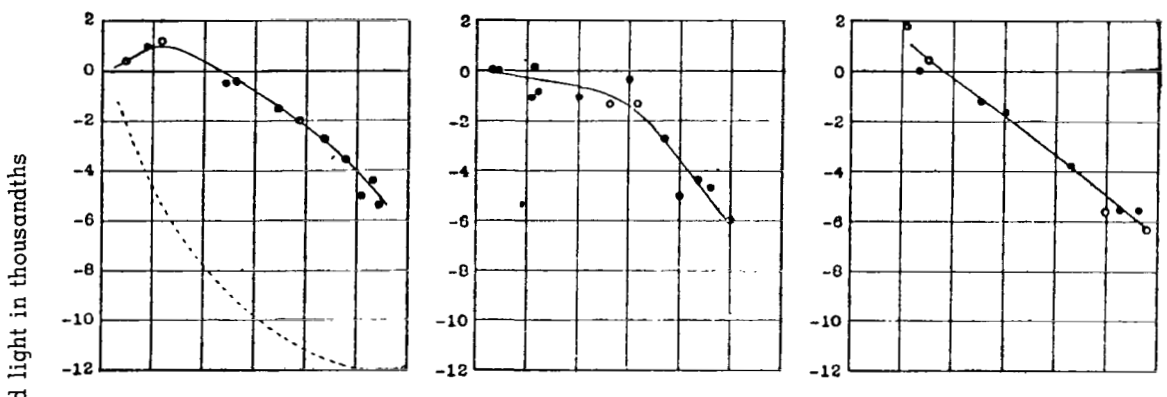

Figure 15. Jupiter (1923)

Figure 16. Jupiter (1924)

Figure 17. Jupiter (1926)

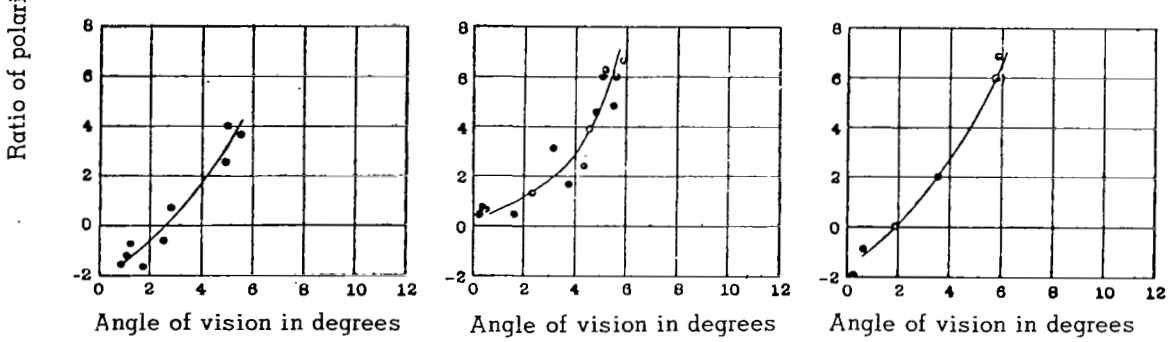

Figure 18. Saturn (1923)

Figure 19. Saturn (1924)

Figure 20. Saturn (1926)

ranging from 15/ to 20/100 of the diameter, it started to linearly increase until it reached its maximum at the very edge. Table 9 shows how the average polarization of the two edges varied, as measured within a width of approximately 15/100 of the diameter. Their differences with the center, at first weak after the 1924 opposition, seem to have rapidly increased to remain almost constant later. The polarization averaged 3.2/1000 at the east, as against 2.4 at the west.

In 1925 and 1926 the results were similar in all respects. The dimensions of the regions differing from the center varied between 10/ and 25/100 of the diameter, but their polarization was always algebraically greater than that of the center, and always algebraically stronger at the west than at the east; before, as well as after, opposition. The setting rim therefore differs systematically from the rising rim. This fact tends to prove that the Sun, in spite of its distance, still exerts a noticeable influence on the atmosphere of Jupiter.

Polar Caps

General Phenomenon

Starting with the first measurements on Jupiter, in 1922, I noticed with surprise the existence, near the poles of the planet, of a very different polarization from that of the center. I first attributed this to instrumental causes. During the month of April 1923 Jupiter was observable under good conditions and I initiated a detailed study of the polarization of the polar caps, by carefully eliminating the secondary spectrum completely from the objective. I discovered the following phenomena:

Plane of Polarization

On the gray caps which surround the poles of Jupiter the plane of polarization is independent of the relative positions of the Earth and the Sun. It remains steady, even around opposition, whereas the plane of vision rotates almost 180°. It is not the same at every point; along the central meridian it is perpendicular to this meridian, and away from this meridian it turns so as to remain parallel to the nearest edge (1).

Ratio of Polarized Light

The ratio of polarized light seems independent on the conditions of illumination. It is maximum at the poles, decreases regularly towards the equator and becomes equal to that of the center at a latitude which can be as low as 35°. (2)

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(1) This property is easily verified at the edge up to 30° from the poles from either side of the central meridian. At these points the two planes of polarization make an angle approximately equal to 60°.

(2) The latitudes adopted here are defined as the angular distance from the point considered to the equator, measured from the center of the planet. For Jupiter and Saturn an accurate definition is necessary, because of their pronounced oblateness.

Variation of the Ratio of Polarized Light with Latitude

I made frequent measurements in 1923 and during the following years along the central meridian, at various apparent distances from the rim. These distances were sometimes measured on drawings or even directly estimated in hundredths of the polar diameter. The error made in this way does not exceed two units. The obtained results are listed in Table 10. The polarization generally decreased from the rim almost linearly and the reader will notice this by examining the graphs of Fig. 14, drawn from the series of values obtained. Exceptions to this rule are as follows. The anomalous polarization of the north cap, instead of disappearing sometimes at a certain well-defined latitude, continued toward the equator with a poorly defined limit. This occurred in particular on 2 August 1926.

On 30 July 1924, at 2300, a gray-cloud, whose polarization was negative and close to that of the center, covered the edge of the north polar cap. The polarization of this cap extended to an unusually small area and ceased abruptly at the edge of the cloud, at a distance from the north pole equal to 11/100 of the diameter.

Extension of the Anomalous Polarization

The regions which had an anomalous polarization were almost as extended in area as the gray caps covering the poles. I have often measured their limits, either directly by noticing the point where the fringes cease to behave like those of the central regions, or with the aid of graphs like those of Fig. 14. The figures found are of the same order of magnitude. They are listed in Table 10, together with the ratio of polarized light of the polar edge. The apparent extension and the extension in latitude were almost always higher at the north than at the south, except during the anomaly of 30 July 1924.

Maximum Polarization

The polarization of the far polar edge was either measured directly, when the images were good, or extrapolated. In 1923 the maximum polarization of the south was always higher than for the north. The difference, close to 20/1000 at the start of observations, became less regular and finally undetectable in 1926. The changes in tilt of the axis of Jupiter do not provide adequate explanation for these changes. The figures vary irregularly because it is difficult to measure the polarization of the far edge, because the image agitation displaces the observed point. Considering only the measurements made with the large refractor, which are more accurate, the polarization of the north edge varied from 53/ to 83/1000 and that of the south edge from 70/ to 83/1000. This shows that the polarization is very high and can be observed even with a narrow fringe Savart polariscope. When the fringes are projected on the planet parallel to the line joining the poles they are visible up to a distance from the edges equal to one tenth the diameter.

TABLE 10
Jupiter – Anomalous Polarization of the Polar Caps

Date and Time			V	Central Regions O	Central Regions P	Polar. Limit F	Polar. Limit φ	N. Edge P	Mean Zone φ	Mean Zone P	Polar. Limit F	Polar. Limit φ	S. Edge P	Mean Zone φ	Mean Zone P	Image Quality and Additional Observations
1923	1 May		2200	0°53'W	16 +0.4	16	38°	..	53°	14	16	43°	..	58°	17	Excellent, Pol. limited to the caps.
	3		2200	0 30 W	16	..	..	..	..	..	..	..	37	..	18	S. cap more extended and more polarized than N. cap.
	30		2200	4 52 E	17 –0.6	..	..	..	..	10	..	..	..	..	15	
	11 June		2100	6 52 E	17 –1.5	17	37	..	..	..	13	49	..	..	..	Pol. exceeds the N. cap, poorly defined.
	24		2100	8 41 E	17 –2.7	21	31	..	..	..	17	43	..	..	..	Polarization limited to the caps.
	3 July		2100	9 31 E	17 –3.5	..	..	..	..	19	..	..	58	..	31	Pol. increases rapidly at the S. pole.
	11		2100	10 7 E	17 –5.1	..	..	30	..	..	..	..	..	..	..	The anomalous pol. extends to the 2 caps.
1924	4 May		0200	6 19 W	81 –1.3	14	42	60	55	30	13	48	73	62	42	Good.
	26		2300	2 16 W	81 +0.2	19	34	..	..	..	16	45	..	..	..	Fairly good.
	2 June		2300	0 39 W	81 0	..	..	57	..	..	..	..	65	..	..	Caps polarized to their limits.
	5		2300	0 8 E	81	20	33	68	..	..	20	37	83	..	..	
	10		0100	0 50 E	81 0	..	..	76	..	..	..	..	80	..	24	Pol. of the two caps almost identical.
	16		2200	2 21 E	81 –0.8	25	26	..	..	..	20	37	..	..	..	Extremely unsteady, ambiguous measurements.
	25		2300	4 1 E	81 –1	..	..	63	..	..	..	..	78	..	..	
	30 July		2300	9 16 E	17 –4.7	11	48	..	..	..	18	41	..	..	..	A grey cloud partly hides the N. cap.
1925	16 June		0100	4 46 W	81 –2	17	38	78	54	33	14	46	80	59	38	Excellent.
	30		2300	2 0 W	81 +0.2	..	..	82	..	..	..	..	62	..	..	Excellent.
1926	21 May		0300	11 30 W	81 –6.3	15	43	..	56	38	14	45	..	58	37	
	31		0300	11 14 W	81	21	34	74	42	37	19	38	72	52	32	
	20 June		0100	9 56 W	81 –5.6	19	37	83	52	28	19	38	85	53	18	Satisfactory.
	2 August		0100	3 0 W	81 +0.5	19	36	81	52	28	14	45	87	58	25	Pol. of the N. cap poorly defined.
	6		0000	2 10 W	81 +1.8	16	41	60	57	35	14	44	60	55	31	
	8 September		2100	5 3 E	81 –1.2	..	..	69	..	..	..	..	73	..	..	Polarization extended more to the N. than S.
	29		2200	8 33 E	81 –3.8	23	31	..	..	..	16	41	..	..	..	
	1 November		2100	11 16 E	81 –5.5	..	..	78	..	..	13	46	73	..	..	

F: Apparent distance to the closest polar edge, expressed in hundredths of the polar diameter.
φ: Planetocentric latitude.
The other symbols are as for Table 5.

Saturn

Conditions of Observation

Saturn comes into view under less varied conditions of illumination than Jupiter, because it gravitates around the Sun at a distance twice as great. At quadratures the angle of vision reaches only 5°50' whereas at oppositions it goes through a minimum between 0 and 17 minutes. Only a small fraction of the polarization curve is available to us. Saturn presents, however, rather different aspects from one year to the next because of the high 28° inclination of its equator, and of its rings, with respect to its orbital plane. On the other hand, the almost constant apparent diameter of Saturn is much smaller than that of Jupiter and reaches only 19" at opposition. Its brightness is also much weaker, so that the separate study of its details necessitates the use of large instruments and requires good images and a fairly transparent atmosphere.

During the observations Saturn remained low above the horizon. At the beginning, in May 1922, Saturn rose at the meridian to 43° above the horizon at Meudon, whereas at the opposition of 1927 its elevation did not exceed 23°. Nevertheless the images were often fairly good, especially in 1925, and permitted the use of a magnification of 900 for the study of the rings. The north pole was first slightly tilted towards the Earth, but a great portion of the southern hemisphere was still visible. The slightly tilted rings were difficult to observe. The north pole became more and more tilted towards the Earth and the southern hemisphere disappeared behind the rings which increased their tilt to a point of greatest extension in 1928.

Central Regions

The polarization of Saturn, as for Jupiter, shows certain anomalies near the edges. It is for this reason that I did not study the average polarization of the disk, but only the polarization of the regions around the center, near the equator and covering approximately a quarter of its surface. This polarization was uniform, and its value is given by Tables 11 and 12.

In 1922 I made some measurements with the 83 cm instrument; most of them without a yellow filter. They apparently were inaccurate and did not give results in agreement. In 1923, being more accustomed to the polarimeter I made a series of more accurate measurements with the 17 cm instrument. The obtained results are shown by the curve of Fig. 18. This curve shows a negative polarization which is weak at opposition, changes sign around 2°40' and then increases rapidly. The observations made in 1924 with the large refractor (Fig. 19) show a positive polarization which is very weak at opposition but rapidly increases. Very few measurements were made in 1925; the polarization followed an intermediate curve to those of 1923 and 1924. The same is true for 1926; represented by Fig. 20. Finally, a few measurements made in 1927 seem to indicate similar variations to those of 1924. All these very close curves differ completely from those of the other planets.

TABLE 11
Saturn – 1922 and 1923, Central Regions

Date and Time				V	O	M	E	P	Observations
1922	15	May	2100	4°48'E	81	2	0	0	
	1	June	2300	5 43 E	81	2	0.1	+ 5.8	Sky becomes overcast
	20		2200	6 6 E	81	5	1	+ 8.8	Unsteady images
	23		2200	6 6 E	81	4	1.5	+ 8.1	Poor images
	29		2200	6 4 E	81	2	0.8	+ 5.5	
1923	14	April	2200	0 49 E	15	4	0.5	– 1.6	
	17		2100	1 6 E	15	1	...	– 1.2	
	18		2100	1 13 E	15	4	0.2	– 0.7	Light cirrus
	23		2000	1 44 E	16	4	0.8	– 1.7	
	1	May	2100	2 34 E	16	4	0.6	- 0.6	Excellent images
	3		2200	2 46 E	16	1	...	+ 0.7	
	30		2100	4 54 E	17	3	0.6	+ 2.5	Cirrus
	1	June	2100	5 1 E	17	2	0.4	+ 4.0	
	11		2100	5 31 E	17	4	1.1	+ 3.6	

The symbols are the same as for Table 5.

Zones and Belts

I often compared, in 1924 and 1925, the clear equatorial zones to the dark northern tropical belt. They always showed identical polarizations except, however, from 15 June to 7 July 1925, when the polarization of the equator exceeded that of the neighboring belt by 0.4/ to 0.9/1000.

On 9 June 1924, I noticed that the clear zone between the wide tropical belt and the northern polar cap (between latitudes 45 and 65) had a negative polarization, opposite to that of the other parts of the disk. This polarization went through a minimum of approximately -3/1000 on June 15, then reversed between 16 and 25 June, but remained very much less than that of the center until July 7, the end of the observation period. This zone showed a clearer and less yellow tint than the equatorial zone. No peculiar phenomenon was observed during the following years.

Polar Caps

In 1923, I examined the poles of Saturn after having observed the perplexing polarizations on the polar caps of Jupiter, in the hope of discovering a similar phenomenon. Unfortunately, the large Meudon refractor was immobilized during the whole year for dome repairs and I had to use the 0.175 m equatorial. In spite of the weak image brightness which precluded the use of a magnification greater than 200, the poles seemed to be markedly more polarized than the equator.

TABLE 12
Saturn – 1924 to 1927

Date and Time		V	O	P	Central Regions		North Polar Cap and Neighboring Regions Anomalous Polarization							Image Quality and Additional Observations
					Polar. Limit		Cap Boundary		N. Edge	Center of Cap		Mean Polar.		
					F	φ	F	φ	P	φ	P	φ	P	
1924 18	April	2100	0°17'	81	+0.5	..	..	..	..	..	..	..	..	..	Strong pol. E.W. on N. cap
20		2200	0 20 E	81	+0.7	23	47°	10	68°	..	82°	23	..	..	Pol. E.W. at pole, rotates with edge
21		2200	0 25 E	81	+0.6	28	42	..	..	22	..	20	..	..	Pol. limited to the tropical band
3	May	2300	1 38 E	81	+0.5	..	..	..	..	22	..	23	..	..	
10		2100	2 18 E	81	+1.3	..	..	..	..	..	..	19	..	..	Pol. of small extension, limited to dark cap
18		2100	3 4 E	16	+3.1	..	..	..	..	..	..	..	..	..	Guess of the dark cap polarization
26		2200	3 45 E	81	+1.8	11	69	11	69	..	77	16	77°	16	Good, the polarization increases to N. edge
2	June	2200	4 19 E	81	+2.4	..	..	..	..	..	..	16	..	..	Cap and polarization of small extension
5		2200	4 31 E	81	+3.9	12	63	12	63	16	..	..	..	..	Fairly steady
9		2300	4 47 E	81	+4.6	9	70	6	76	..	85	20	..	..	Good, negative zone φ = 47° to 63° P = −1.6
15		2200	5 7 E	81	+6	10	67	10	67	..	77	13	77	13	Negative zone P = −3.5
16		2100	5 10 E	81	+6.2	9	69	10	67	..	..	..	..	..	Negative zone P = −2
23		2100	5 29 E	60	+4.8	..	..	..	..	..	..	..	..	..	
25		2200	5 33 E	81	+6	..	..	..	..	..	..	..	..	..	Zone 47° to 63° P = +2
7	July	2100	5 53 E	81	+6.6	..	..	..	..	..	..	7	..	..	Zone 47° to 63° P = 0, cap of small ext.
1925 21	April	2300	1 6 W	81	+0.3	31	40	9	75	..	86	25	62	17	
2	May	2200	0 18 E	81	....	33	38	11	70	29	84	29	..	..	Good, entire N. hemisphere grey-blue
..	.....	....	.....	..	....	..	..	..	..	..	..	..	..	..	Constant pol. on N. cap
16		2300	1 36 E	81	0	32	39	..	..	29	..	29	..	..	Constant polarization on N. cap
3	June	2300	3 19 E	81	+2	32	39	..	..	26	..	..	..	..	Pol. extends to N. edge

TABLE 12 (Continued)

Date and Time			Central Regions			North Polar Cap and Neighboring Regions Anomalous Polarization									
						Polar. Limit		Cap Boundary		N. Edge		Center of Cap		Mean Polar.		Image Quality and Additional Observations
			V	O	P	F	ϕ	F	ϕ	P	ϕ	P	ϕ	P	
1925	5 June	2100	3°29'E	13	....	29	43°	..	..	..	..	..	64°	13	Calm and windless, hardly sufficient light
	15	2200	4 16 E	81	....	26	48	..	..	30	..	17	..	..	Excellent, pol. extends to edge
	30	2100	5 9 E	81	+4.9	29	43	..	..	20	..	13	..	..	Slightly unsteady
1926	13 May	2100	0 15 W	81	−1.9	15	67	11	75°	..	..	..	83	7	Very poor
	20	2200	0 39 E	81	−0.9	17	64	..	..	14	..	..	80	6	Poor
	31	2200	1 50 E	81	0	21	60	6	86	16	..	15	71	5	Steady at times
	19 June	2200	3 30 E	81	+2	16	65	8	82	..	..	13	82	5	Fair, then poor
	1 August	2000	5 46 E	81	....	16	65	..	..	..	..	14	82	7	Steady, but foggy sky
	2	2000	5 47 E	81	+6	..	..	..	..	..	..	10	..	..	Poor and pale
	7	2200	5 50 E	81	+6.9	..	..	..	..	..	..	16	..	10	
1927	8 May	2300	1 50 W	81	+0.7	11	78	..	..	..	..	..	90	5	Pol. of small extension
	14	2300	1 14 W	81	+0.8	11	78	..	..	..	..	..	90	3	Cap very dark and very small
	19	2300	0 43 W	81	....	11	78	..	..	..	..	..	90	7	Poor, sky becomes overcast
	25	0000	0 16 W	81	....	9	82	8	85	..	..	..	..	10	
	4 July	2200	3 46 E	81	+1.6	15	70	..	..	..	..	..	85	5	Poor, very strong wind
	7 September	2000	5 39 E	81	+5.5	..	..	..	..	..	..	..	..	..	Poor, clear sky

F: Apparent limit distance to the North edge, expressed in hundredths of the polar diameter.

ϕ: Corresponding planetocentric latitude.

The other abbreviations are the same as for Table 5.

North Polar Cap

I observed the north polar cap of Saturn with the large refractor during each opposition from 1924 to 1927. On 18 April 1924, Saturn went through opposition and the polarization of the central regions was almost undetectable. On the regions neighboring the north pole the polarization was, on the contrary, very high and its plane seemed parallel to the major axis of the ring.

Plane of Polarization

The measurements made on the following days showed that the plane of polarization did not depend on the direction of the Sun. Along the central meridian it was perpendicular to the axis of Saturn to within 2°. Away from either side of the central meridian it rotated so as to remain in every point almost parallel to the closest part of the rim. On 3 May 1924, at 30° east and west from the central meridian, measurements made near the rim gave deviations of 21° and 30°. On 4 May 1925, the corresponding deviations measured 20° from the meridian, were 17° and 18° respectively. These are phenomena quite similar to those found for Jupiter.

Extension of the Regions of Interest and Ratio of Polarized Light

The series of observations is summarized by Table 12. On 20 and 21 April 1924, the polarization reached 23/1000 at the pole, remained appreciably constant between the pole and the north edge but decreased almost linearly towards the south, to become equal to that of the center at a distance from the north edge corresponding to 28/100 of the polar diameter, in other words at latitude 42. The regions of anomalous polarization went far beyond the dark cap which was located on the latitudes above the 68th degree approximately. The same was true of May 3. Starting from May 10, however, the anomalous polarization decreased at this cap. Its extension decreased even more on June 9 so that at the end of the observation period its extension was 9/ to 10/100 of the diameter. That is, its extension covered the latitudes above the 70th degree. The polarization had at the same time decreased and its maximum varied between 15/ and 20/1000.

On 21 April 1925, after resuming the measurements, I was surprised to find the anomalous polarization again very much extended and as high as in April 1924. Its extension was 31/100 of the polar diameter and went down to latitude 40. The same was true until June 30, the end of the observations period. The dark cap retained its extension of April 1924. The ratio of polarized light was from 25/ to 30/1000 near the pole and remained constant on an area from 6/ to 8/100 of the polar diameter, then decreased regularly. From 13 May to 7 August 1926, the anomalous polarization remained. However, it was limited to 16/100 of the diameter, or to latitude 65, except for May 13 when it went down to the 58th degree. The dark patch, smaller than the preceding year, reached only the 83rd degree. The ratio of polarized light was on the average only 5/ to 10/1000, and on the edges 14/1000.

In 1927, the anomalous polarization decreased further, just exceeding the gray cap, and covered an extension less than 11/100 of the diameter, i.e., latitudes above the 80th degree. It

increased somewhat at the end of the month, and reached the 70th degree on July 4. The ratio of polarized light was not constant and its average value ranged from 3/ to 10/1000. Thus the north polar regions of Saturn show phenomena which are quite similar to those which I described for Jupiter, but which are much less constant; their extensions and their intensities go through very significant and simultaneous changes.

Southern Hemisphere

In the spring of 1923 the southern hemisphere, like the northern hemisphere, seemed to be more polarized than the equator, but I was not able to verify this observation with certainty, because I could only use the 175 mm aperture refractor. In 1924 the southern hemisphere, visible between the latitudes 27 and 70 with the large refractor, did not appear to be noticeably different from the center. In 1925, regardless of the fact that the visible part was still smaller (latitudes 38 to 68) the polarization reached 5/1000 at opposition; a value which is of the same order of magnitude as that of the corresponding northern regions. The southern polar regions of Saturn seem to show therefore, effects similar to those of the northern polar regions, and these phenomena are also subject to significant variations. In order to verify this conclusion we must wait for the year 1935 when the south pole will again tilt towards the Earth.

The Rings of Saturn

First Measurements

First I studied in the spring of 1923 the polarization of the rings as a whole, around the middle part of the arches. Since, as I mentioned before, the large refractor was immobilized, I first made use of the 175 mm instrument. In spite of their low precision, due to insufficient light, the measurements revealed polarizations roughly perpendicular to the plane of vision and ranging between –2/ and –6/1000. In 1924 I frequently examined the same regions with the large refractor equipped with an 350 magnification eyepiece. This was not sufficient for a good separation of the polarizations of the two rings. The ratios of polarized light found in this manner are listed in Table 13 and are plotted as a function of the angle of vision in Fig. 21. These results confirm generally those of 1923. However, they are not too satisfactory. No regular curve can be plotted through points whose ordinates seem to vary in an incoherent way.

I also made a few measurements in other points of the ring, especially from either side of the peaks and on the frontal part of the planet, without reaching agreement. The leading branch of the ring seemed to be noticeably more polarized than the lagging branch. Around opposition the plane of polarization seemed to turn along the ring in the same direction as the radius of the planet. I thought I could explain these appearances by attributing the polarization of the ring, or at least part of it, to the light it receives from the illuminated hemisphere of Saturn. The first measurements of 1925 showed that, in reality, the phenomena are more complicated and that in order to obtain clear results it is indispensable to separately study the two concentric rings which

TABLE 13
Two Rings of Saturn as a Whole

Date and Time	V	O	Ratio of Polarized Light A. W.	A. E.	Images
1923 1 May 2200	2°34'E	16	....	– 2.1	
1 June 2100	5 1 E	17	....	– 6.6	
11 2100	5 31 E	17	....	– 2.8	
1924 20 April 2200	0 20 E	81	– 2.8	– 2.9	
21 2200	0 24 E	81	– 2.3	– 2*	
3 May 2300	1 38 E	81	– 3.6	– 4.5	
10 2100	2 18 E	81	– 3.7	– 3.6	Very unsteady
18 2100	3 4 E	17	....	< 0	
26 2200	3 45 E	81	– 2.4	– 2.7	Unsteady
2 June 2200	4 19 E	81	– 3	....	
5 2200	4 31 E	81	– 2.9	– 3.5	Fairly steady
9 2300	4 47 E	81	– 3	– 4	Steady
15 2200	5 07 E	81	– 3.3	– 4.2	
16 2100	5 10 E	81	– 3	....	Unsteady
23 2100	5 29 E	60	– 5.3	– 2.8*	
25 2200	5 33 E	81	– 1.8	– 1.9	
6 July 2100	5 52 E	60	....	– 4.4	
7 2100	5 53 E	81	....	– 4	
1925 21 April 2300	1 6 W	81	– 2.2	– 2.6	Fairly good
2 May 2200	0 18 E	81	– 5*	– 4.2	Good measurement
4 2200	0 26 E	81	– 1.8	– 2	Wind rises

A. W.: West or preceding arch.
A. E.: East or following arch.
The other symbols are the same as for Table 5.

are separated by the Cassini division. This study was initiated on 5 May 1925, and was continued in May and June of the same year, in May and June 1926, and from May to September 1927 with magnifications ranging from 550 to 900. The obtained results are summarized in Table 14.

Inner Ring (B)

The ring within the Cassini division is easy to study separately near the peaks because of its great width and its great brightness. In 1925, a magnification of 550 was applied to medium quality images and this was always sufficient. In 1927, the ring opening increased and I was able to make some good measurements up to the September quadrature, in spite of the highly mediocre images and of the fairly high atmospheric absorption.

TABLE 14
The Saturn Rings Studied Separately

Date and Time			V	X	Ratio of Polarized Light				Plane of Polarization				Image Quality and Additional Observations
					Inner		Outer		Inner		Outer		
					A.W.	A.E.	A.W.	A.E.	A.W.	A.E.	A.W.	A.E.	
1925	4	May	2300	0°26'E	146°5	.....	.....	− 3.4*	− 2.4	235°	239°5	258°	215°	
	5		2200	0 31 E	141.3	− 4.5	− 4.8	− 3.8	− 7.7	227	223	244	221*	Strong wind
	17		2000	1 36 E	118.3	− 4.5	− 5.0*	.....	− 7.3	202*	.....	.....	197*	Fairly good
	3	June	2300	3 19 E	112.4	− 3.5	− 3.4*	− 2.1	− 3.5	....	.....	192	183*	
	15		2200	4 16 E	111.5	− 2.2*	− 3.1	− 4.2*	− 5.9*	....	.....	205.5	193	Excellent
	30		2100	5 9 E	110.2	− 4.1*	− 4.0	− 2.4	.....	....	.....	230	203	Fairly good
1926	20	May	2200	0 39 E	126.8	− 5.0*	− 4.2*	.....	− 6.9*	219*	213*	232*	200*	Mediocre, then better
	31		2200	1 50 E	112.1	.....	.....	.....	.....	207*	195*	235*	189*	Fairly good at times
	19	June	2200	3 30 E	108.5	− 5.3*	− 4.4*	− 5.7*	− 8.2*	195*	195.5*	202*	199*	Fairly good, then mediocre
1927	14	May	2300	1 14 W	90.5	− 4.7	− 4.8	− 2.6	− 8.7	180	181*	190*	161	
	19		2400	0 43 W	84.7	.....	.....	.....	.....	176*	174*	.....	....	Poor, sky becomes overcast
	24		2400	0 16 W	49.6	− 3.7*	− 3.4	− 5.7*	− 7.5	139	140	170	135	
	25		2400	0 13 W	28.0	.....	.....	.....	.....	120*	.....	.....	....	Mediocre, hazy sky
	26		2400	0 13 E	0.0	− 2.4	− 2.6	− 2.4	− 4.8	267	261	281	198	
	15	June	2400	2 5 E	.....	− 4.5	− 4.4	.....	.....	....	.....	.....	....	Unsteady and pale
	21		2200	2 39 E	.....	− 4.3	− 3.5	.....	.....	....	.....	.....	....	Unsteady
	22		2200	2 45 E	.....	.....	− 4.2	.....	.....	....	.....	.....	....	Rough
	27		2200	3 11 E	.....	.....	− 4.1	.....	.....	....	.....	.....	....	Mediocre
	4	July	2200	3 46 E	.....	− 3.4	− 3.6	.....	.....	....	.....	.....	....	Strong wind
	11		2300	4 17 E	.....	− 3.3	− 3	.....	.....	....	.....	.....	....	Very pale
	2	September	2000	5 44 E	.....	.....	− 1.1*	.....	.....	....	.....	.....	....	Pale, mediocre measurements
	5		2000	5 41 E	.....	.....	− 2.2	.....	.....	....	.....	.....	....	
	6		2000	5 40 E	.....	− 1.6	− 1.8	.....	.....	....	.....	.....	....	Mediocre, then better
	7		2000	5 39 E	.....	− 2.1	− 2.0	.....	.....	....	.....	.....	....	Bright, excellent measurements
	21		....	5 12 E	.....	.....	− 3.2	.....	.....	....	.....	.....	....	Bright, but unsteady

V: Angle of vision. X: Position angle of the plane of vision. A.W.: West or preceding arch. A.E.: East or following arch.
Numbers with an asterisk are the results of single measurements.
All measurements were made with the large telescope, free aperture: 81 centimeters.

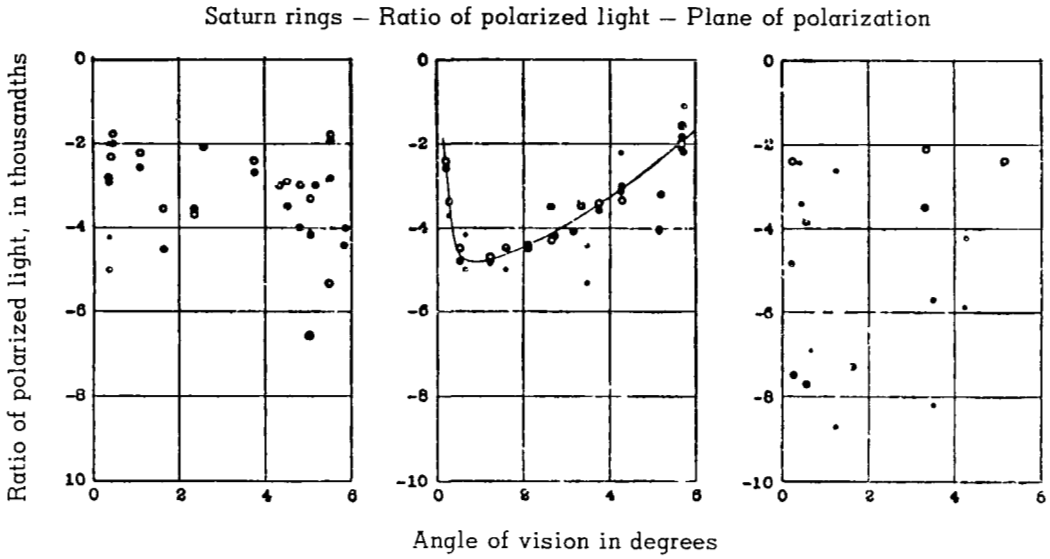
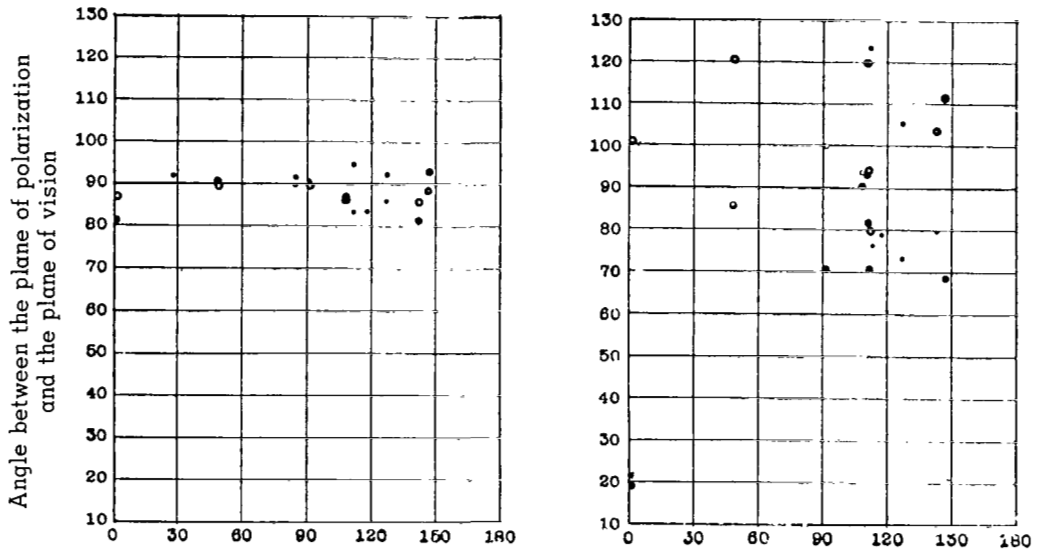

Saturn rings — Ratio of polarized light — Plane of polarization
Ratio of polarized light, in thousandths
Angle of vision in degrees

Figure 21. The Ring System

Figure 22. Inner Ring

Figure 23. Outer Ring



Points obtained for the East arch { result of a single measurement • • • ; average of several measurements • • • }

Points obtained for the West arch { result of a single measurement • • • ; average of several measurements o o o }

Figure 24. Inner Ring

Figure 25. Outer Ring

Plane of Polarization

The ratio of polarized light of the inner ring was always sufficient (greater than 2/1000) to permit the determination of its plane of polarization with an error less than approximately 10°. The results are given in Table 14. Near the peaks, this plane was always perpendicular to the plane going through the Sun to within less than 10°, in spite of the fact that the plane of vision rotated sometimes very rapidly, up to the point of sweeping more than 20° per day around the opposition of 1927. This remarkable fact is shown in the graph of Fig. 24 which was obtained with the position angle of the plane of vision as abscissa, and the angle between the plane of polarization and the plane of vision as ordinate.

Ratio of Polarized Light

Table 14 gives the ratio of polarized light as found near the peaks of the inner ring. The points of curve 22 represent all the obtained values. The thicker dots correspond to the average of several readings. They are remarkably well aligned, although they refer to the two arches of the rings and to three different years. Consequently the ratio of polarized light is exactly the same on the two peaks and depends only on the angle of vision. The curve showing its variations is very different from those which were so far studied. The ordinates are negative for the small angles, which would make the curve similar to that of the Moon, but its minimum of 5/1000 is reached for 1° only (instead of 11° for the Moon). The polarization then algebraically increases almost linearly and changes sign probably between 7.5° and 8° for an observer situated on Mars or Jupiter. The angle of vision reached its smallest value of 11' during the opposition of 1927, when at that time the polarization was still 2.5/1000. The angle of vision became zero only in July 1931, and therefore we cannot know the origin of the curve before this date. We can however determine it in a more accurate way than for all the other planets because of the small apparent diameter of the Sun which, when seen from Saturn, subtends an angle of only 3'11". The inner ring often seemed to me to be more polarized on its inner edge than near the Cassini division, and also slightly more polarized on its leading branch than on its lagging branch, but these are very small and consequently uncertain differences.

Outer Ring (A)

The ring outside the Cassini division is more difficult to observe than the inner ring. It is slightly narrower and much darker and the eye is often constrained by the brightness of the inner ring. In order to perform correct measurements good images are necessary as well as a good atmospheric transparency and a strong magnification. Under these conditions the 83 cm aperture is enough to yield clear but less accurate results on the outer ring than on the inner ring. Most of the time I employed the 900 magnification which darkened the images a little too much. The magnification of 550 was sometimes employed but seemed somewhat insufficient.

Plane of Polarization

As shown in Table 14 the plane of polarization of the outer ring is very different from that of the inner ring. It coincides neither with the plane of vision nor with its normal and, in addition, its orientation is different on both arches. These phenomena greatly surprised me. For this reason I tried to determine if they were instrumental errors, but I could find no instrumental cause. When the polarimeter is turned by 180°, the results remain the same. If the polarimeter is oriented such as to have equal fringes on one of the arches of the outer ring, this equality ceases to occur when either the other arch or the inner ring is brought into the field center.

The graph of Fig. 25 summarizes the obtained results. Here the abscissas are the angles of vision and the ordinates the angles between the plane of polarization and the plane of vision. This shows that the angle between the two planes is generally close to 80° for the east arch, and from 95° to 120° for the west arch.

Ratio of Polarized Light

The ratio of polarized light has the same lack of symmetry, as shown on Fig. 23. It seems to vary irregularly, from 2/ to 5/1000 for the west arch and 4/ to 9/1000 for the east arch. It is therefore the east arch, whose plane of polarization is least deflected, which shows the greatest polarization.

These very curious results seem to be quite definite, but their interpretation is made difficult by the insufficient precision of the measurements. I shall, however, try to explain them in Chapter VII, after studying the polarizing properties of various substances in the laboratory.

PART TWO–RESEARCH IN THE LABORATORY

Introduction

The preceding chapter has led us to consider the planets as sources of numerous and varied polarization phenomena.

It is very important to find the explanation of these phenomena and to draw a few conclusions concerning the nature of the ground, the clouds, and the atmospheric conditions of the planets. The most reliable way to obtain such a result would be to compare the polarization found on these planets to those yielded by different substances illuminated and studied under equivalent conditions.

With this comparison in mind, we shall first summarize the principal results obtained up until now on the polarization by solids, and the polarization by clouds of solid or liquid particles.

CHAPTER IV. HISTORICAL BACKGROUND

Polarization by Solids

General Study

The polarization of light scattered by solids was recognized relatively late. In particular, it escaped the attention of Arago who, as we have seen, attributed the polarization of the Moon to the presence of an atmosphere on our satellite. It was studied for the first time by Laprovostaye and Desains (1) in 1852. These physicists analyzed the light scattered by plates whose surfaces were either ground or covered with various substances, and they obtained the following results. When the plate is normal to the incident rays, the ratio of polarized light is maximum for the rays scattered very obliquely, it decreases very rapidly when the observer approaches the normal, and it is generally not noticeable below 40°.

The ratio of polarized light varies greatly depending on the substance. At 85° from the normal it is equal to:

0.22 for platinized platinum,

0.47 for black ground glass,

0.76 for lampblack.

Illuminated at an incidence of 30°, these three substances produce a relatively strong polarization in the direction of the simply reflected ray, whereas lead chromate, cinnabar, and sulfur do not yield any noticeable polarization.

At an incidence of 70° all these substances polarize light in the direction of simple reflection, with a ratio of:

0.25 for lampblack,

0.44 for lead chromate,

0.45 for white lead,

0.50 for sulfur,

0.52 for cinnabar,

(1) LAPROVOSTAYE and DESAINS, Annales de chimie et de physique, Vol. 34, third series, 1852, p. 215.

0.61 for platinized platinum,

0.64 for black ground glass.

At grazing incidence the polarization of these substances is zero, and it is possible to find for all substances an angle for which the polarization is maximum. Every completely ground surface polarizes light along the plane which goes through the source. Porcelain polarizes light sometimes normally to the plane at high angles of incidence.

In 1900 Wright (1) studied the scattering of light by compressed powders. He observed that, except at high angles of incidence, his plates did not polarize light but instead depolarized it completely. In 1903 Umow (2) used colored substances such as coloring powders, papers that were impregnated with their solution, etc. For all these substances the polarization of the scattered light is most intense for the colors most strongly absorbed and vice versa. In 1910 Salet (3) studied the polarization of the back-scattered rays. He found it to be zero for sandstone, and noticeable but very weak for plates of melted sandstone illuminated very obliquely. In 1860 Verdet (4) established the following theory on the polarization by scattering. For substances with non-compact surfaces, such as lampblack and platinized platinum, the only effect present is the scattering which is considered as being due to a reflection at the surfaces of convex granules. When the granules are transparent, the rays which are reflected once at the surface are not the only ones received; those which are reflected several times on different planes, essentially within the substance, are also received. "If the incident light is natural, the scattered light will be composed of rays polarized in all planes, without any regularity, and will be natural light. If the incident light is polarized light, all the reflections will tend to change the plane of polarization in a great number of different ways and the scattered light will still be more or less depolarized."

In 1924 Woronkoff and Pokrowski (5) tried to check this theory. They admit that the maximum polarization of light scattered by the surface of substances occurs at an angle ϕ given by Brewster's law: $\tan \phi = n$. The light coming from the interior of a substance can be considered as unpolarized. It must be proportionally greater for the small angles of incidence, which must result not only in a weakening of the polarization, but also in moving its maximum towards the larger angles. The authors checked these conclusions experimentally and found, especially for colored papers, that the maximum polarization was weaker and the corresponding angle higher for the least absorbed radiations.

Minerals

As stated in Chapter I different minerals have been studied for the purpose of comparing them to the lunar ground. In 1890 Landerer (6) examined a great number of polished volcanic

(1) WRIGHT, Annalen der Physik, 4th series, Vol. 1, 1900, p. 17.
(2) UMOW, Physikalische Zeitschrift, Vol. 6, 1905, p. 674.
(3) SALET, Thesis, 1910, p. 58.
(4) VERDET, Optique Physique, Vol. 2, p. 488.
(5) WORONKOFF and POKROWSKI, Zeitschrift für Physik, 12 Dec. 1924, Install. 30, 2nd book, p. 139.
(6) LANDERER, On the Polarization Angle of Igneous Rocks, C.R. Vol. 111, 1890, p. 210.

rocks in order to determine their angle of maximum polarization and to compare it to the angle he had found for the Moon. He obtained values which range between 30°51' and 33°46'. For one of these rocks, vitrophyre, the angle of maximum polarization was 33°18' and only 1' above the mean value obtained for lunar seas. The author concluded that the greater part of the Moon seas must be composed of this rock.

In 1922, Salet (1) studied different rocks; in particular, marbles which had been polished to various degrees of finish. He proved in this way that the angle of maximum polarization varies with the finish of the surface and approaches the angle of incidence value when the surface is polished to a higher degree. The knowledge of the angle of maximum polarization is therefore not sufficient to determine the nature of a mineral.

A more extensive work was published in 1926 by Barabascheff (2). This author first studied glass ground to increasingly finer grains and observed that the coarser the grain, the smaller the effect of polarization and the broader the maximum. On the other hand, he obtained for ground rock salt very strong polarizations when the grains were coarse. Carborundum powders of different degrees of coarseness yielded polarizations which increased with the coarseness of the grains. The curves drawn from figures he obtained on lavas and basalts have a sharp maximum lying between 43% and 88%. For porphyries and granites the maximum is broader and varies between 61% and 81%. Sands yielded quite different polarizations, the weakest of which occurred on white sands, and sand containing clay, with an albedo close to the albedo of the light regions of the Moon, yielded a maximum polarization of the order of 15%. According to the author their presence in these regions is probable. The mineral whose property would most resemble those of the lunar seas would be a porous lava with a maximum polarization corresponding to an angle of vision of approximately 100° and reaching the value of 43%.

Polarization by Cloudy Media

In 1820 and 1822, Arago (3) observed on 22° solar halos a weak but noticeable polarization by refraction. His cloud observations permitted him to conclude that the light from the clouds should not be polarized light, but that in order to study this correctly the observer must be almost in contact with the clouds (4). "During his ascensions with Mr. Bixio, Mr. Barral studied the clouds intensely and found no polarization, neither by transmission nor by reflection."

In 1868, Tyndall (5) studied the polarization of artificial clouds. He found in very thin blue clouds, which were produced by sunlight on amyl nitrite vapor, a strong polarization along a plane passing through the light source and maximum at 90° from the rays. When the cloud becomes white

(1) SALET, L'Astronomie, p. 406, 1922.
(2) BARABASCHEFF, Astronomische Nachrichten, Vol. 229, p. 7, 4 September 1926.
(3) ARAGO, Oeuvres, Vol. 10, p. 562.
(4) ARAGO, Oeuvres, Vol. 19, p. 282.
(5) TYNDALL, Proceedings of the Royal Society, Vol. 17, 1886, pp. 92-232.

the polarization decreases more for the blue rays than for the red rays. On coarser dusts, neutral points can be observed. Ammonium chloride vapors yield, as they grow thicker, a maximum which moves toward the incident rays: "An aqueous cloud reverses the polarization."

In 1888, Soret (1) noticed that the polarization of condensed water vapor is "negative," "perpendicular to the plane of vision," when the angle of vision is near 90°. It changes sign when the observer is at 70° from the source, becomes very strong at 45°, then decreases. "These figures," he stated, "depend on the abundance of particles, on their thicknesses and on a few other circumstances." For a jet of water struck against a solid he found the polarization to be positive and maximum at the two faintly colored rainbows and found a neutral point at 100°. According to him, "The clouds are too opaque to be compared to those of laboratory tests." For a sea of clouds seen from the top of a mountain, he found a polarization which was zero at the anti-solar point, then fairly strongly positive, changed sign around 3°, then became positive after going through a neutral point lying between 12 and 20° depending upon the direction under consideration. It reached a maximum around 40° (white rainbow) and finally changed sign at about 90° to reach a negative maximum around 135°.

In 1908, Mie (2) calculated the ratio of polarized light scattered in various directions by colloids whose grains behaved like semi-conductor spheres. For gold grains he found that above 100 $m\mu$ the light scattered at 90° is almost entirely polarized in the plane passing through the source. When the particle becomes thicker the natural light increases rapidly along the direction of propagation, whereas the light back-scattered close to the source acquires an opposite polarization. In 1924, Shoulejkin (3) calculated, by the Mie method, the light scattered in all directions by spheres of relative index 1.32, for the following three cases:

1. Very small diameter compared to the wave length;
2. Diameter equal to $\frac{\lambda}{\pi}$;
3. Diameter equal to $\frac{3\lambda}{\pi}$.

In the first case, the plane of polarization always goes through the source. At 90° from the latter, the scattered light is minimum, its polarization is maximum and total. In the second case, the plane of polarization always goes through the source, the scattered light is weaker in the direction of the source, stronger in the opposite direction. The maximum polarization, somewhat less intense than in the first case, is slightly displaced by angle in the opposite direction to the source.

The third case is very different. Almost the whole light is scattered in a direction opposite the source within a cone of 60° radius. The back-scattered light is polarized in a plane going

(1) SORET, Annales de physique et chimie, Vol. 14, 1888, p. 503.
(2) MIE, Annalen der Physik, 1908, Vol. 25, p. 377.
(3) W. SHOULEJKIN, Philosophical Magazine, 48, 1924, pp. 307–320.

through the source. The ratio is weak and does not exceed 50/1000. It passes through zero for an angle of vision of 35°, reaches a negative minimum of 750/1000 for an angle of 100° and becomes zero opposite the direction of the light source.

The case of very thick spheres was also studied, but without taking into consideration the rays which go through several reflections inside the spheres.

Present Status of the Problem

The work summarized in this chapter shows that the substances which surround us give rise generally to very different polarizations. We shall see, however, that in spite of the interest these substances present, this work is often not complete enough or accurate enough to explain the results obtained on the planets. The measurements made on solids have demonstrated the influence exerted by their degree of polish and by their absorbing power on the polarization in the neighborhood of its maximum. These measurements were not made, however, on light backscattered in a direction close to the source. No inversion similar to the ones shown by the Moon and Mars has been reported. The measurements made on minerals were generally done on rocks which polarize light more than the planets, none of the obtained curves can be compared with those of the planets and, lastly, the precision of the results does not go beyond 1%, which is insufficient. The observations on droplets, in particular those of Soret, bring into evidence effects due to the thickness of the droplets which result from diffraction effects. These observations show the existence of inversion points similar to those of Venus, but the results obtained still differ greatly from those of this planet, so that no conclusion can be drawn. Soret noticed that the results depend greatly upon the thickness of the cloud, but this influence needs to be determined. In order to explain the shape of the polarization curve of Venus it is necessary to undertake a more complete study on a great variety of samples.

Under these conditions it is necessary to take measurements on various substances, with a precision equal to that of the astronomical observations, and with a sufficient number to permit the construction of a complete curve in each of the cases under study. A choice had to be made among a considerable number of substances capable of being studied in the form of various physical states, powders of different grain sizes, solids with different degrees of polish, etc. Hoping to find some general information to serve as a guide to my research I first studied glass powders and powders of metallic salts chosen in such a way as to observe any influence of the index of the grains, of their shape, and when applicable, of their absorption or birefringence. The measurements were later made on natural minerals which were either cut with a rough face, or powdered. The choice was directed towards those which seemed to give polarizations similar to those of the Moon and of Mars. Later I examined cloudy media, but this was limited to clouds of water droplets and to a few ice fogs which are most frequent in nature.

CHAPTER V. EXPERIMENTAL APPARATUS

General Equipment

Construction

The apparatus used for most of my measurements is as follows: The substance S (Fig. 26) is located at the center of a goniometer with one arm carrying the light source and the other the polarimeter. The source is a half-watt lamp of 6 volts, 100 candles. Two lenses of 40 mm focal length each, B and C, send a greatly magnified image of its filament upon the substance, through a prism D by total reflection. This prism is followed by a twin crystal plate E, designed to suppress the weak polarization of the lamp and that emanating from the lenses (this plate will be described later). A circular diaphragm F of 12 mm diameter limits the aperture of the source. The polarimeter has a biconvex lens G of 18 cm focal length, which gives an image of the most illuminated area of the sample upon an eyecup H of 2 mm diameter, placed against the eyepiece of the polariscope (the eyepiece lens having been removed). The focus in front of lens G is occupied by a diaphragm I of 3.5 mm diameter. This diaphragm limits the field to a portion close to the axis and subtending an apparent diameter of approximately 70'. At the same time it facilitates the vision of the fringes which appear inside it and in the same plane. The source is located at 45 cm from the surface under study. From this surface the source subtends an apparent diameter of 1°30'. The diaphragm of the polarimeter subtends a diameter of 0.25'. Their angular distance or angle of vision is given by the pointer J, movable on the circle K. This angle can go down to 1°30'. Below this value the planes of vision of the various points of the source are very different, which would make the resulting polarization much weaker than if the source was a point source.

Twin Depolarizer Plate

This plate is made of two quartz plates cut parallel to their optic axes (instead of quartz I actually used two plates of cleaved gypsum). Their thicknesses are in the ratio of 2 to 1 and they are glued together with Canada balsam in such a way that their optic axes make an angle of 45°. This set behaves as follows: Let a linearly polarized light fall on the plates. Let (Fig. 27) OX, OY, OX' and OY' be the axes of the two plates, β the angle between OX' and OX, α the angle between the incident linear vibration OA and OX. Four coincident vibrations OB, OB_2, OC and OC_2 emerge from the second plate.

Let n and n' be the principal indices of the plates, e and e' their thicknesses. The four vibrations go through the respective retardations

$$ne + ne' \qquad ne + n'e' \qquad n'e + ne' \qquad n'e + n'e'.$$

When e' = 2e the retardations of the last three with respect to the first are

$$2(n' - n)e \qquad (n' - n)e \qquad 3(n' - n)e.$$

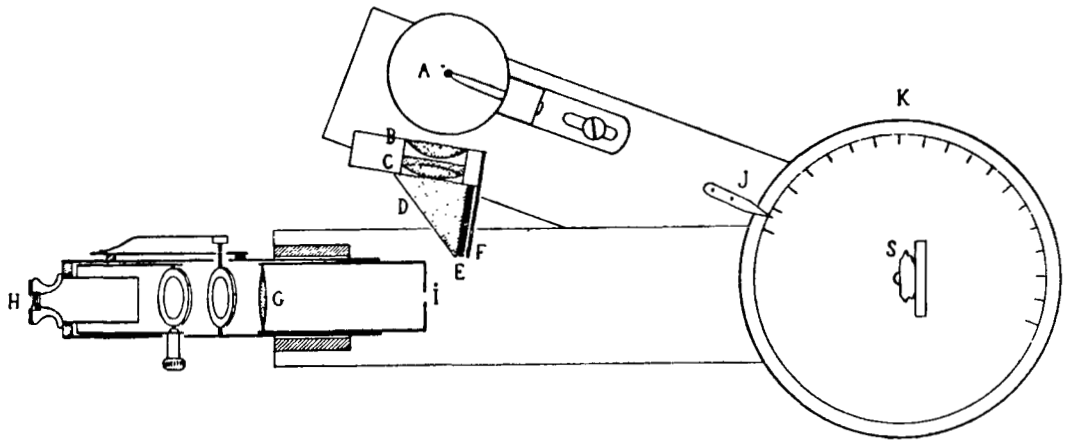


Figure 26. Goniometer for the Study of Polarization by Scattering

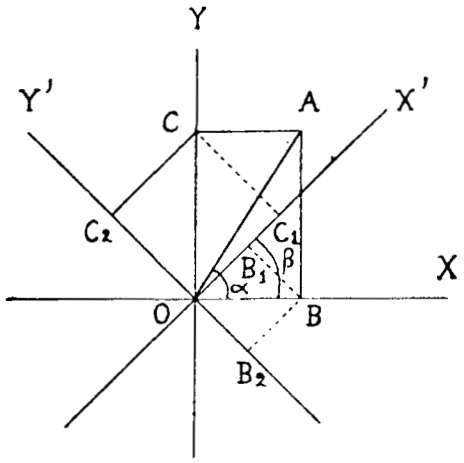


Figure 27. Twin Depolarizer Plate

If (n' – n)e is sufficiently large (greater than 10 wavelengths) these vibrations give no visible interference pattern in white light. Their intensities add. Two beams emerge polarized respectively along OX' and OY', with intensities

$$OB_1^2 \quad OC_1^2$$

for the one, and

$$OB_2^2 \quad OC_2^2$$

for the other. But we have

$$OB_1 = OA \cos \alpha \cos \beta \qquad OC_1 = OA \sin \alpha \sin \beta$$
$$OB_2 = OA \cos \alpha \sin \beta \qquad OC_2 = OA \sin \alpha \cos \beta$$

Also

$$\cos \alpha = \sin \beta = \frac{\sqrt{2}}{2}$$

therefore

$$OB_1^2 + OC_1^2 = \frac{OA^2}{2} \qquad \text{and} \qquad OB_2^2 + OC_2^2 = \frac{OA^2}{2}$$

The two together are equivalent to natural light of intensity OA equal to that of the incident light.

When a highly polarized source of light is examined with a Savart polariscope through the twin plates, no fringes are seen at the field center. On each side of the center other fringe patterns appear along directions corresponding to the compensation by the birefringent Savart plates of the path differences introduced by the twin plates, to within a few wavelengths. Since the measurements were made at the field center these fringe patterns do not come into play and light behaves as if it were perfectly natural.

Orientation of the Substance

In order to study a mineral it is sufficient to cut it roughly along a plane and to secure it with soft wax on a support located at the goniometer center, such that the cut face is parallel to the axis of the goniometer. When the sample is very inhomogeneous it is cut roughly in the shape of a sphere of 6 mm diameter, supported by a very thin steel wire. A small electric motor rotates it around the axis of the goniometer. In this way an average polarization is obtained of the various constituents of the mineral under study. To study a powder, the axis of the goniometer is positioned vertically and the powder is supported by a small plate parallel to this axis. To study thin vapor jets for example, the jets are located at the center of the goniometer.

Study of Light Scattered Very Close to the Source

The astronomical observations which I made, in particular those made on the inner ring of Saturn, show that the rays scattered by certain substances at an angle of only 12' from the light source are still noticeably polarized. The device described above does not permit measurements below 1°30'. In order to achieve angles as small as possible the apparent diameters of the polarimeter aperture and of the source had to be reduced, and the brightness of the source increased, together with the distance and the size of the substance under study.

I therefore constructed the following device. The substance under study S (Fig. 28) is made into a plate 15 to 20 cm wide, and placed in a very dark room. It is illuminated by a diaphragm A of 2 mm diameter, preceded by a twin crystal plate B necessary for depolarizing the light and similar to the one described (French page 102). A lens C of 80 cm focal length, preceded by a polar

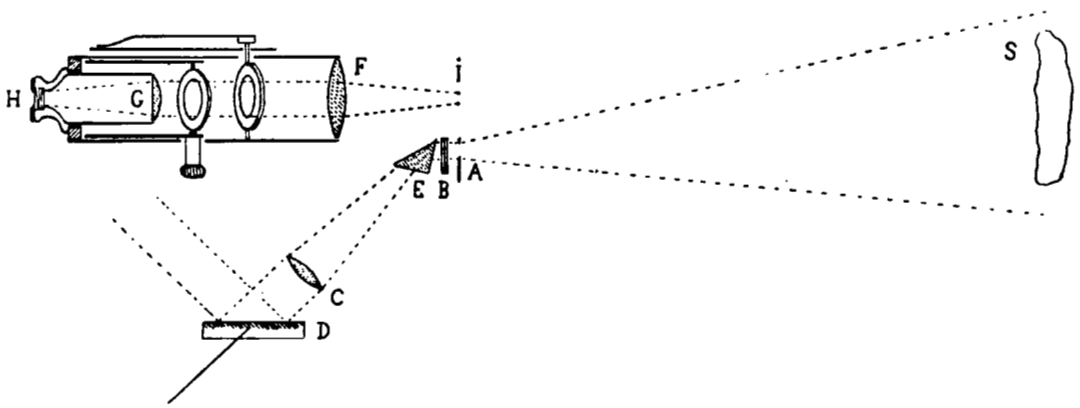


Figure 28. Set-Up for Small Vision Angle Measurements

siderostat D, forms on the diaphragm A an image of the center of the Sun through a very small prism E (by total reflection). The objective of the polarimeter is a lens F, of 6 cm focal length. The eyepiece is a similar lens G. The set gives a full scale image at infinity of the substance S. The eyepiece-polariscope has a diaphragm H of 2 mm diameter. A full-scale image of H, namely I, is formed outside the polarimeter by the set of lenses. The polarimeter is supported by a jack which allows it to be directed on the substance and to bring the image I of its diaphragm to a distance of 4 mm from the diaphragm A of the source. The angle of vision can thus be lowered to 2'48". In order to change the angle, the polarimeter and its support needs only to be moved. It is easy to compute the angle by measuring directly the distance between the source diaphragm and the image of the polarimeter diaphragm.

CHAPTER VI. RESULTS OBTAINED ON TERRESTRIAL SUBSTANCES

Homogeneous Transparent Powders

I first studied glass powders and powders of metallic salts sprinkled in thick layers on small plates. The polarizations obtained depended very little on the orientation of the powder surface, as long as the angle between the latter and the incident rays or the rays scattered toward the polarimeter was not too small. For this reason the measurements which helped to draw the curves were taken for an orientation of the powder surface approximately normal to the bisecting line of the angle between the direction of the source and that of the polarimeter.

Influence of the Refractive Index

Fig. 29 shows the curves obtained for powdered crystals of the following substances:

Sodium nitrate (indices 1.585 and 1.33)

Sodium chloride (index 1.544)

Ammonium chloride (index 1.64)

Barium chloride (indices 1.63, 1.64 and 1.66)

Lead nitrate (index 1.78)

For these substances the polarization is very weak or even undetectable between 0 and 20° and it passes through a maximum around 150°. These, and some of the following curves, have widely dispersed points when the angle of vision exceeds approximately 100°. This is because the powder or the mineral under study sometimes have one of their faces oriented in such a way as to strongly polarize and reflect an appreciable number of incident rays in the direction of the polarimeter.

The polarization of the light studied as a whole can be modified if this face does not have an area which is negligible compared to the area of the rays going to the eye of the observer.

Figures 30 and 31 refer to powdered calcite and to precipitated chalk (1) of indices 1.49 and 1.66 respectively. The shapes of these first seven curves, and in particular the abscissa of the maximum and the corresponding ratio of polarized light, do not seem to depend on the indices, as they would otherwise do in the case of polished materials. When illuminated normally by the completely polarized light these powders scatter back, in the direction of the source, a partially polarized light. The proportion of residual polarized light clearly depends on the birefringence of the grains. This proportion is very weak when the indices are very different. The reader will

(1) This powder was obtained by the cold precipitation of a diluted solution of calcium chloride by a solution of sodium carbonate. The grains must therefore be calcite rhombs.

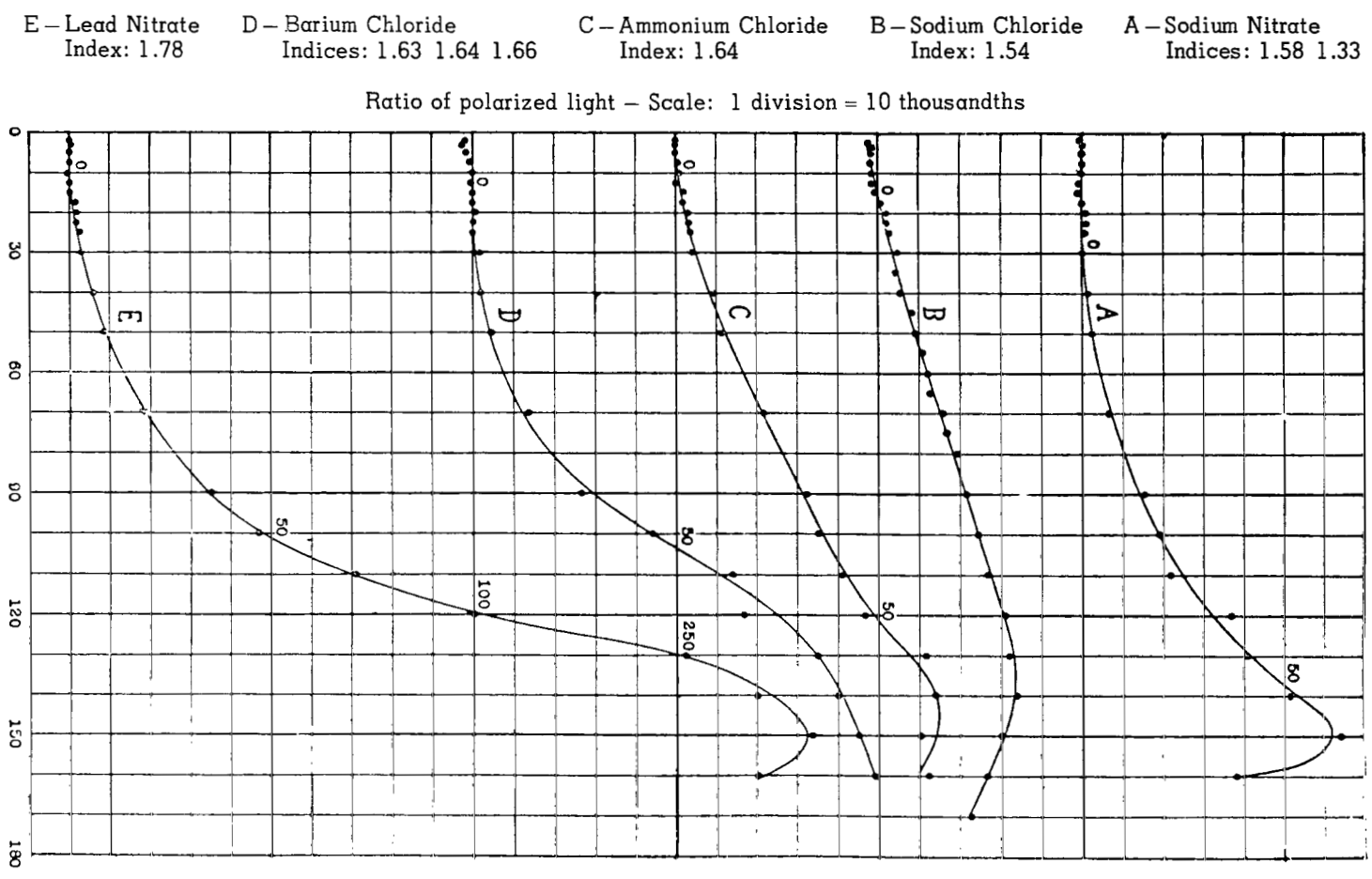


Figure 29. Powdered Crystals

A – Cinnabar, illuminated with blue light
B – Cinnabar, illuminated with red light

Indices 1.49
1.66

Scale: 1 division = 50 mm

Figure 32. Powdered Cinnabar

Figure 31. Precipitated Chalk

Figure 30. Powdered Calcite

Figure 33. Magnesia Deposit

notice this by consulting Table 15. The weakest values (18/ and 22/1000) were found on sodium nitrate powders and on precipitated chalk whose grains, examined under a microscope with polarized light, have the colors red and green. The grain thickness must necessarily play a role. For the same difference of indices the residual polarization must be weaker for thicker grains.

Influence of the Grain Shape

The shape of the polarization curves seems to depend more on the grain shape than on the index, as can be seen by comparing the curves for powdered calcite and precipitated chalk (Figs. 30 and 31). The influence of the grain shape is clear from Fig. 34, relative to glass of index 1.52. The curve A was taken for a powder obtained by crushing this substance. The curve B corresponds to the same powder made into 0.5 mm diameter spherules by first melting the glass. The curve C refers to one of these spherules studied separately. The curve for the crushed glass has a regular shape which recalls that of powdered crystals. It has however, polarizations almost twice as great as that of powdered sodium chloride, although the indices of the two substances are very close. Opposed to this, the curve for the spherules is very complicated. In addition to the usual maximum around 140°, it is wavy and has a very sharp maximum at 20° from the source. These anomalies are easily explained by examining the next curve, taken for an isolated spherule. For this curve at 20° from the source the same maximum is found. It corresponds to a rainbow produced by the rays undergoing a single reflection inside the spherule and it coincides with an intense maximum of scattered light. Around 40° only the rays reflected outside the spherule are present and the polarization is minimum, then increases regularly with the angle. This minimum is also present on the curve for the spherule powder. At approximately 95° the rays are refracted and negatively polarized. They reach a maximum polarization and a high intensity around 105°. For the same angle the curve for the spherule powder shows only a slight drop. This is because the refracted rays must necessarily go through the spherelets in their lower layers so that they can rarely avoid passing through another spherule.

Another puzzling curve is plotted for magnesia which was obtained by burning a tape of magnesium under a glass plate until the deposit on the plate was completely opaque (Fig. 33). The polarization is very strong for the small angles, becomes fairly noticeable around 5', then reaches a negative minimum around 40' and reverses its sign at about 25°. The shape of this curve can be attributed to the size of the grains which are very small and made partially spherical by the fusion. The shape varies with the deposit thickness.

Influence of Grain Absorption

An example of this influence is seen on the two curves of Fig. 32 taken for powdered cinnabar (indices for red light 2.8 and 3.1). The curve B was obtained with a red filter which allows

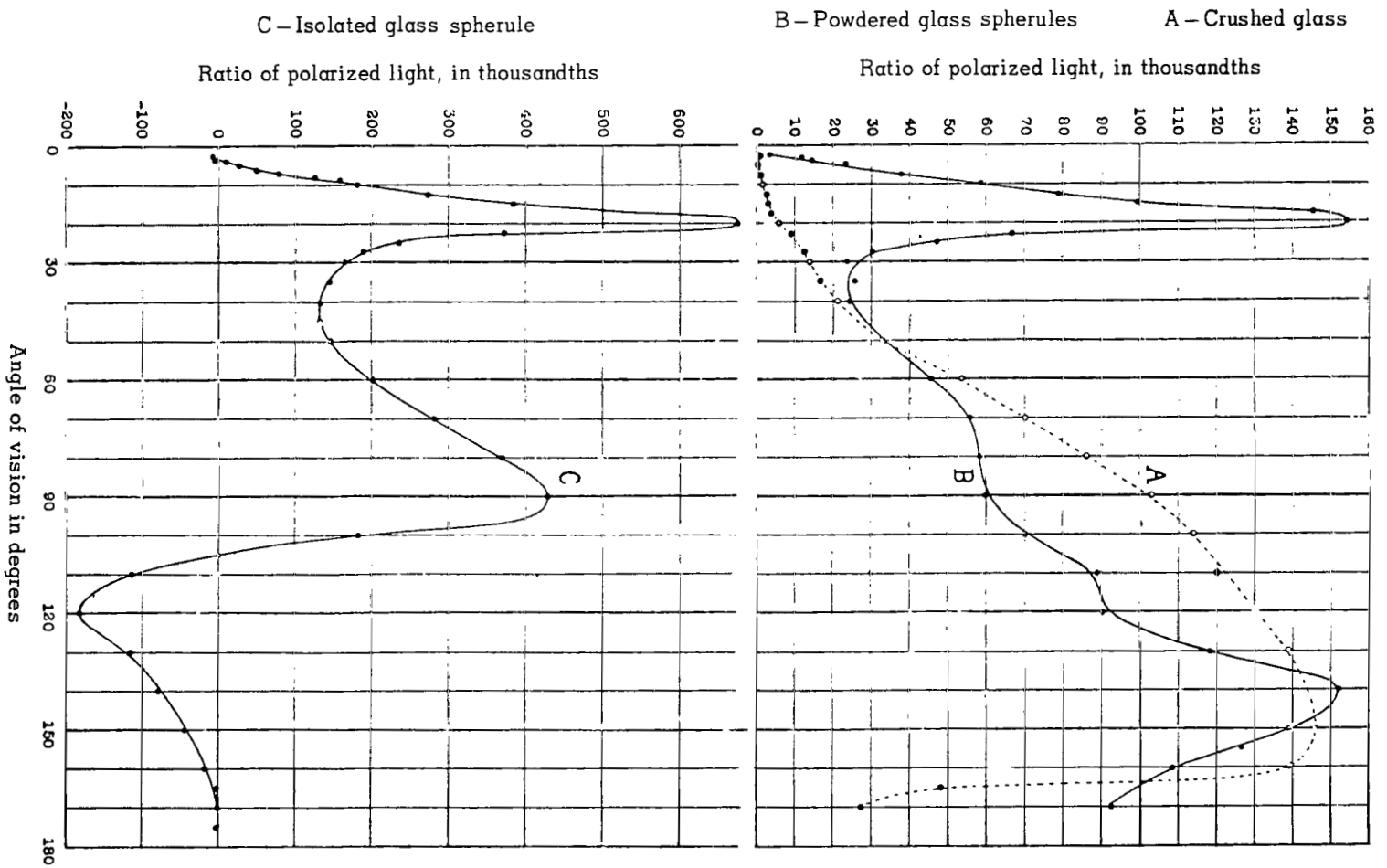


Figure 34. Polarization Given By Glass Grains (Index 1.52)

the rays which have not been appreciably absorbed by the powder to pass through. Curve A was obtained with a blue filter through which the powder seemed to be completely dark. For the central part of A the scale of ordinates was reduced to 1/5. The curve B is similar to that of other transparent metallic salts. The polarization is maximum for 160° where it is equal to 68/1000. The curve A reaches its maximum for 123° where the polarization is 420/1000, slightly more than six times the previous value.

The light which comes from inside the powder, examined through the red filter, has therefore a much weaker polarization than the light which is reflected at the surface, which exists only through the blue filter. The resulting effect is that the polarization of the total light is considerably decreased and the polarization maximum is shifted toward the greater angles, as was indicated by Woronkoff and Pokrowski. On the other hand, the curve for the blue light has a negative branch between 0 and 15°. This negative polarization has never been mentioned, and we shall see later that it is part of a very general effect for solid materials which absorb light. When this powder is illuminated with a completely polarized light the residual polarization varies with reciprocal of the absorption. It is 55/1000 for red light and 598/1000 for blue light.

Snows

Since snow is the most abundant crystalline powder in nature I have used it in many polarization measurements. These were made at night in the Meudon Observatory yard. The curves obtained are similar to those of other crystals but their shapes varied with the state of fusion of the snow, as seen from the curves of Fig. 35. The melting snows give polarizations which increase with the amount of water contained. The partially melted snows which were refrozen have variable polarizations, often smaller than that of freshly fallen snow.

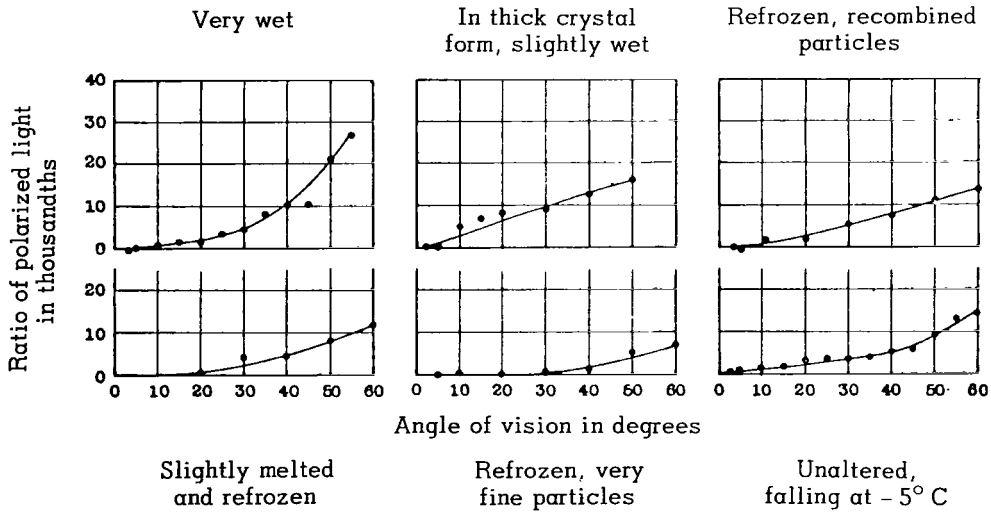


Figure 35. Samples of Snow at Various Stages of Fusion, as Normally Observed

The polarization due to the scattering of light by homogeneous powders appears to be an extremely complicated phenomenon. It varies as a function of the angle of vision according to a relationship which depends on:

1. the mean index of the grains,
2. the difference between their indices if they are birefringent,
3. their absorbing powers,
4. their sizes which affect both their birefringence and their absorption and regulate the diffraction effects,
5. their shape.

The residual polarization of the rays scattered back to the (completely polarized) source depends also on all these quantities. It varies with the index and the absorption power, and varies reciprocally with the birefringence and the grain thickness. With regard to the study of natural minerals which are not homogeneous and which have an even more unknown constitution than that of the crystalline powders, a reliance on theoretical considerations seems completely impossible. It is therefore in a purely experimental way that we must look for rocks which behave, under the polarimeter, like the celestial materials.

Minerals

Sedimentary Rocks

Chalk. The curve A of Fig. 36 is obtained from a chalk sample having an albedo of 0.79 (1) and roughly cut in the form of a 7 mm sphere (see the arrangement described on French page 103). For the small angle the shape of the curve resembles that of powdered calcite (Fig. 30), but with a more pronounced negative branch. The polarization, first negative and very weak, reaches its minimum at approximately 15° and changes sign at 30°. At the great angles this polarization remains weak and the shape of the curve resembles that of precipitated chalk (Fig. 31).

Clays. A rotating sample of gray-green clay from the Paris basin, with an albedo of 0.17, gave the curve B (Fig. 36). At the angle of 3.5° the polarization is 6/1000 and seems close to its

(1) This quantity will later be defined as the brightness of the material with respect to that of a perfectly scattering white body, the surfaces of the two being normally illuminated and examined along directions close to the normal. I measured this quantity to within a few hundredths with the polarimeter by comparing the studied substances with a white screen of magnesia.

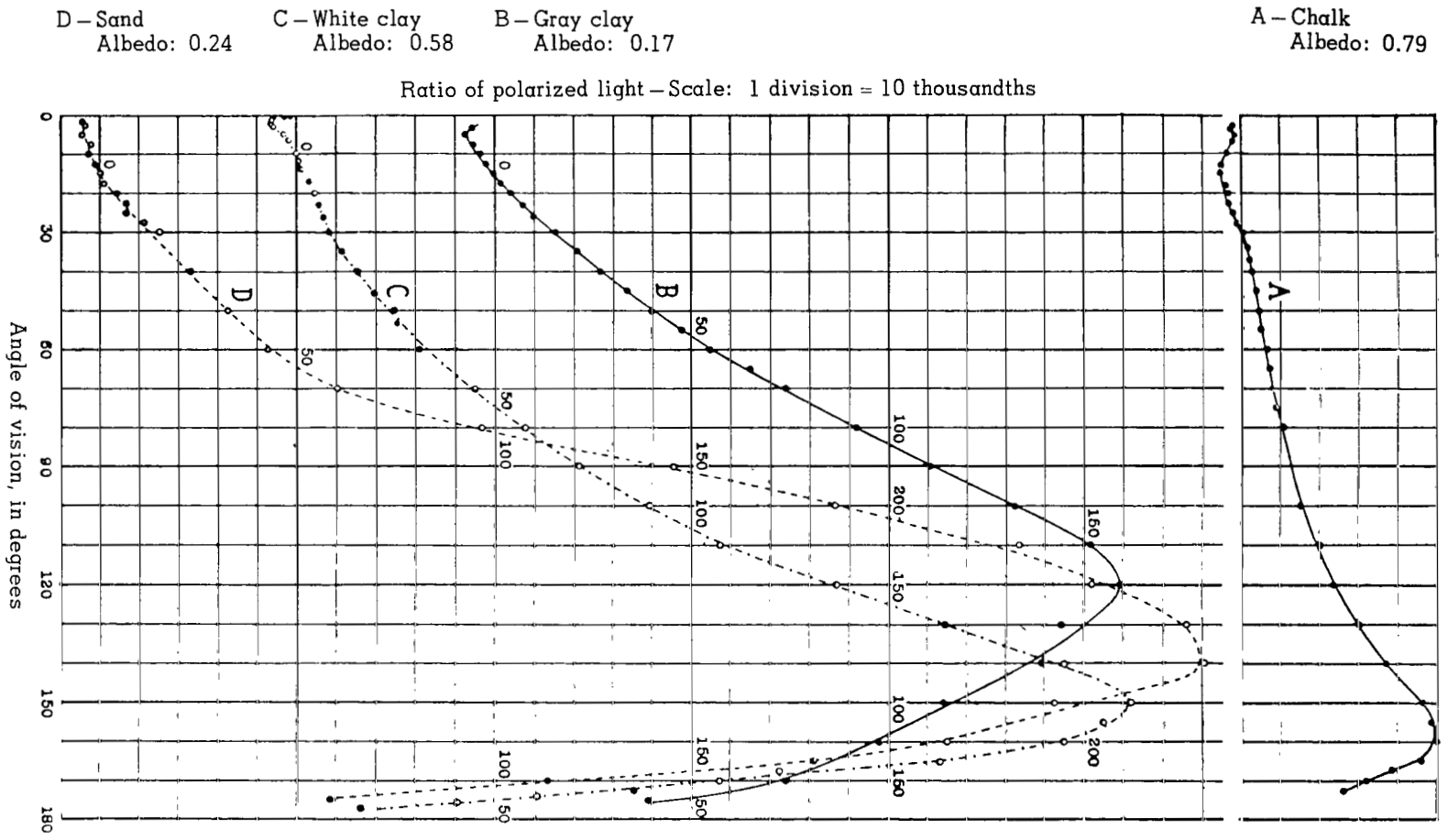


Figure 36. Sedimentary Rocks { A, B and C: rotating sample
D: symmetrically observed sample

minimum. It rises and changes sign at 15°. Its positive maximum is reached at 120°. A rotating sample of white clay from the Yonne (France), with an albedo of 0.57 gave the curve C (Fig. 36). This curve has a very weak negative branch and a very sharp positive maximum around 150°. It is somewhat remarkable that this clay gave stronger polarizations than the other clay, in spite of the fact that its albedo is much higher. The measurements corresponding to the small angles indicate a polarization of -6/1000 at 0.5°.

Sands. I also studied sea sands collected on a beach at Vendée (France) (curve D, Fig. 36). The negative branch is still present. The polarization which is necessarily zero in the direction of the source because of symmetry seems to reach its negative minimum very rapidly.

Igneous Rocks

Since all these curves are fairly different from those of the Moon and Mars, I did my research on igneous rocks and especially on eruptive rocks whose existence on our satellite seems to be more probable.

Rocks Having Metallic Reflection. Fig. 38 gives the curves C, D and E obtained on the three powdered minerals: magnetic iron oxide, iron pyrite, and galena. All three have a very high maximum between 140° and 145°. The pyrite curve is zero between 0° and 12°, that of the magnetic iron oxide has a slightly negative branch, and that of the galena sample has a very sizeable negative branch.

Granites and Porphyries. These substances were studied by the rotating sample method. The curves A and B (Fig. 37) are for a dark blue-green porphyry, with a 0.13 albedo. The curve B (Fig. 39) corresponds to a gray-grained white granite of 0.14 albedo. Note on all three, weakly negative branches whose minima seem to be reached for an angle less than 2°.

Basalt. A rotating sample of basalt gave the same results (curve A, Fig. 39).

Quartz Sandstone. A rotating sample of sandstone formed by welded quartz grains of 0.34 albedo gave the curve D (Fig. 39), which has a shape close to that of the white clay (curve C, Fig. 36) but with an almost zero negative polarization. This curve strongly resembles the curves for the powdered salts the mineral of which dominates the composition of Sandstone Quartz. The maximum occurs at a smaller angle, undoubtedly because the absorbing power is greater.

Red Sandstone. A rotating sample of red sandstone gave the curve C (Fig. 39), which exhibits very different behavior. The polarization is strongly negative with a very sharp minimum at about 7° to 8°, the sign changes at 17° and the positive polarization is strong and reaches a maximum of 315/1000 at 130°. In the neighborhood of this maximum the polarization varies greatly with the color of light; it is strongest, as expected, for the most strongly absorbed radiations.

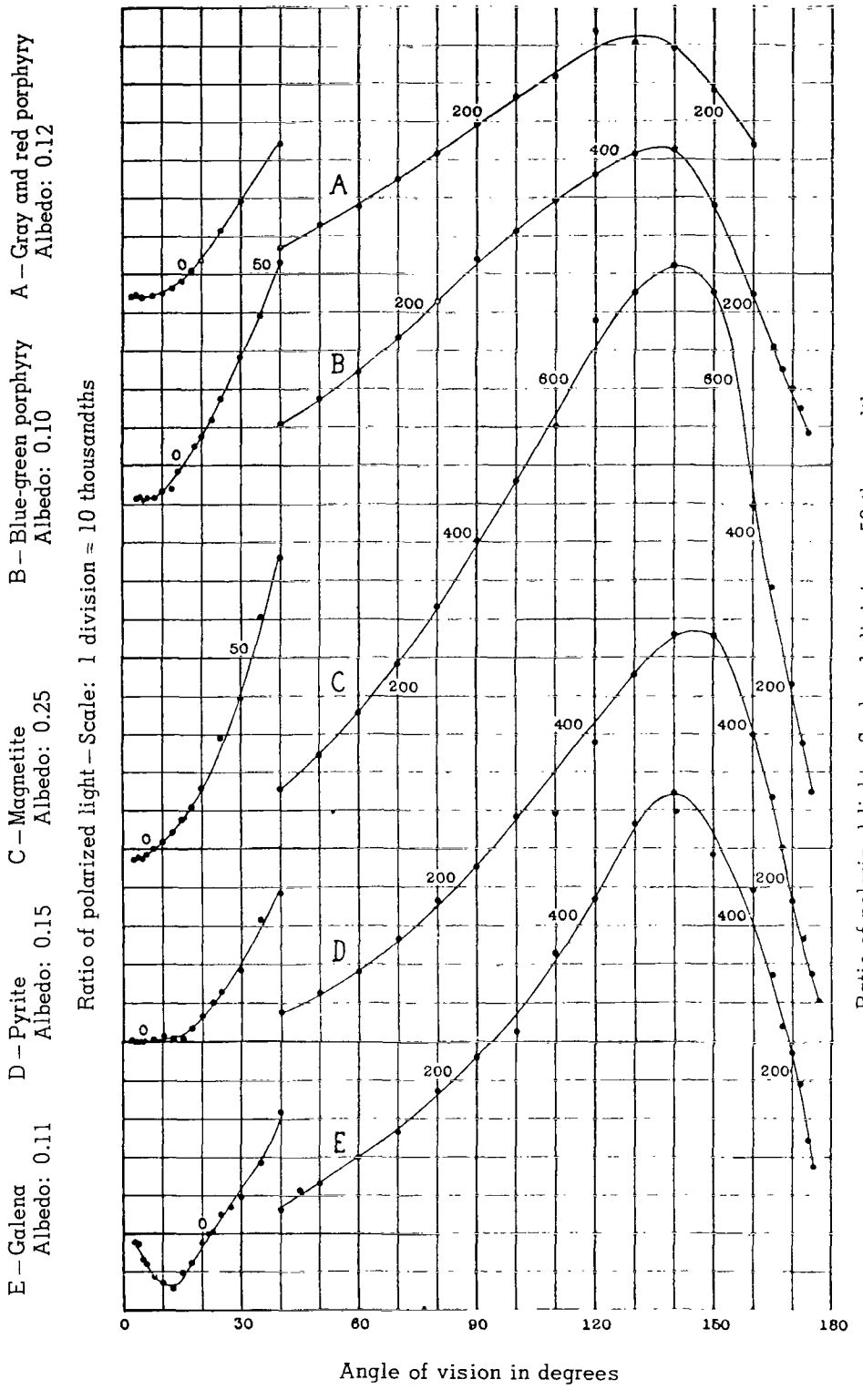


Figure 37. Rotating Porphyry Samples

Figure 38. Powdered Minerals

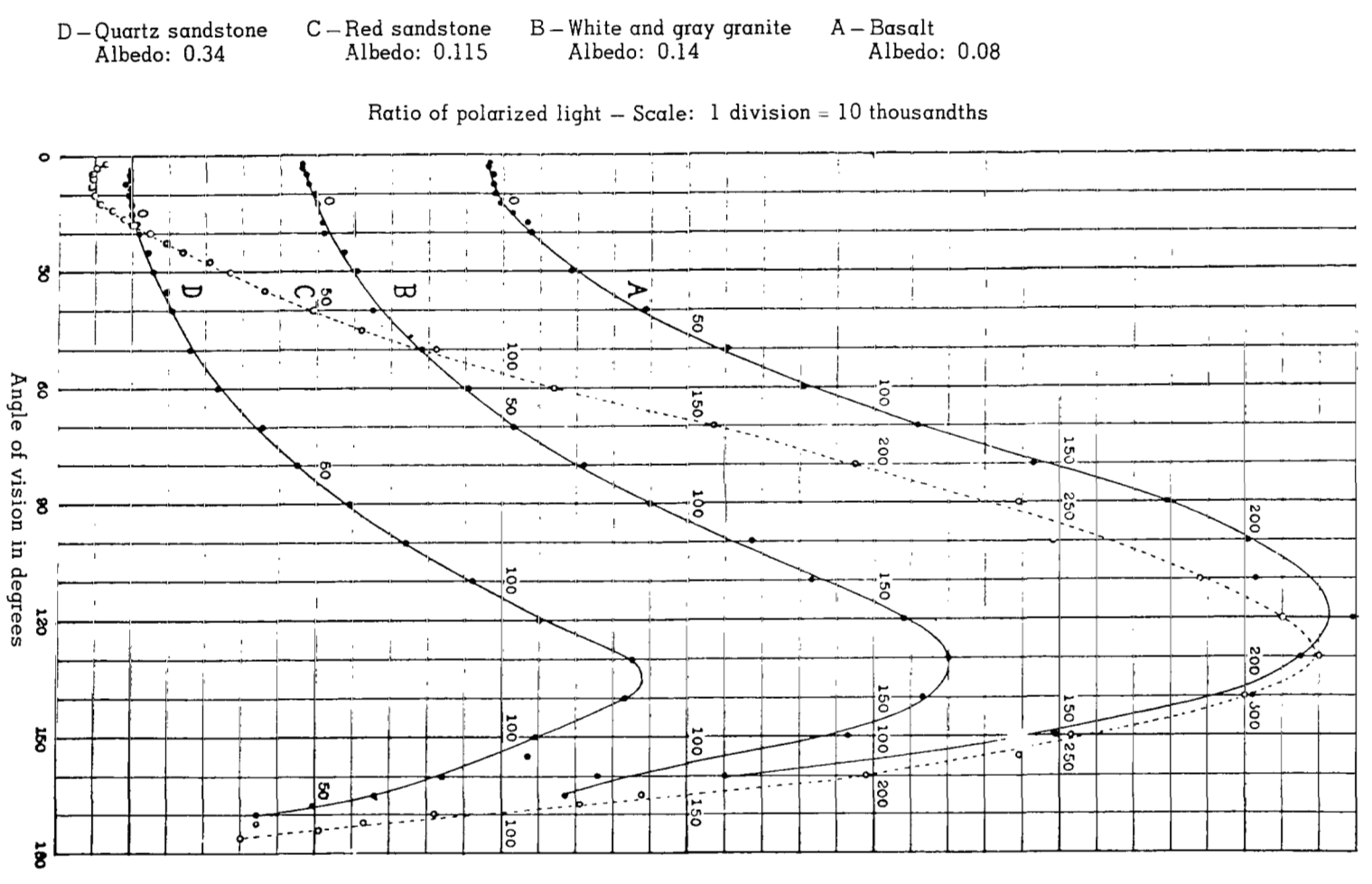


Figure 39. Rotating Samples of Igneous Rocks

Lavas. I studied a lava sample from Volvic (France) and seven lava samples from Mount Vesuvius (1). All samples were oriented with their cuts normal to the bisector between the incident ray and the ray scattered toward the polarimeter. They gave fairly different results, as seen from the curves of Figures 40 and 41. These curves correspond to lavas of decreasing albedos. Generally, when the albedo decreases the maximum polarization tends to increase.

The porosity seems to play an important role in the curve shape. The very porous lavas generally have a relatively weak maximum polarization which is slightly displaced towards the small angles of vision. Their negative branch is always larger. The strongly vitrified lavas have a relatively strong positive polarization and a weak negative branch which sometimes is nonexistent. It seems that the porosity of the lava increases the negative branch, the abscissas of the minimum and the inversion point. These properties are worthy of verification on powdered samples. The curves A', B' and C' (Fig. 40) are for samples A, B and C which have been ground into fine powders (0.1 mm to 0.2 mm grains). For all three, the negative polarization is higher, the inversion angle is higher, and the abscissa of the maximum is lower. The maximum polarization is higher for the highly porous lava A, whereas it is considerably lower for the lavas B and C. These changes are not only due to variations in the hues, since the pulverization increased the albedos of the lavas B and C, while decreasing that of lava A; instead they are largely due to changes in the porosity.

Volcanic Ashes. I studied a great number of volcanic ashes ejected by Mount Vesuvius during the rains of 1872, 1906 and 1908. The curves of Figures 42 and 43 are for a few samples whose albedos decrease from 0.22 to 0.05 and whose colors vary from brown-red to gray-blue. These curves have special characteristics which differentiate the volcanic ashes from the other rocks, as shown in Table 15. They all have a greater negative branch than that of the previously mentioned substances. The inversion angle is still between 17 and 23°, and seems to be higher for the clearer ashes. The abscissa of the minimum varies in the same way between 6 and 10°, and the amplitude of the minimum is the greatest for the darkest ashes; it goes from -8/ to -14/1000. The positive polarizations are generally much weaker than for the other substances of the same albedo. The abscissa of the maximum is small and varies from 90 to 130°, but it increases when the albedo decreases, which is opposite to what we found for the homogeneous powders. The residual polarizations which are obtained with a completely polarized incident light are close to those of the lavas and granites; they lie between 0.220 and 0.440 and increase very regularly when the albedo decreases. Finally, except on the darkest ashes, the product of the residual polarization and the albedo is greater than for the other substances.

Causes of Negative Polarization

We found that almost all absorbing solid materials and even a few very white materials, such as chalk and magnesia, polarize light normally to the plane of vision when the observer is placed

(1) These lava samples, as well as the samples of volcanic ashes which will be studied later, were offered to me by Mr. Malladra, Director, Mount Vesuvius Observatory, to whom I would like to express my sincere gratitude.

Very porous red-brown lava
C – Albedo 0.082 C' – Albedo 0.15

Gray lava, slightly crystalline and porous
B – Albedo 0.15 B' – Albedo 0.17

Gray porous lava, large white crystals
A – Albedo 0.23 A' – Albedo 0.17

Ratio of polarized light – Scale: 1 division = 10 thousandths

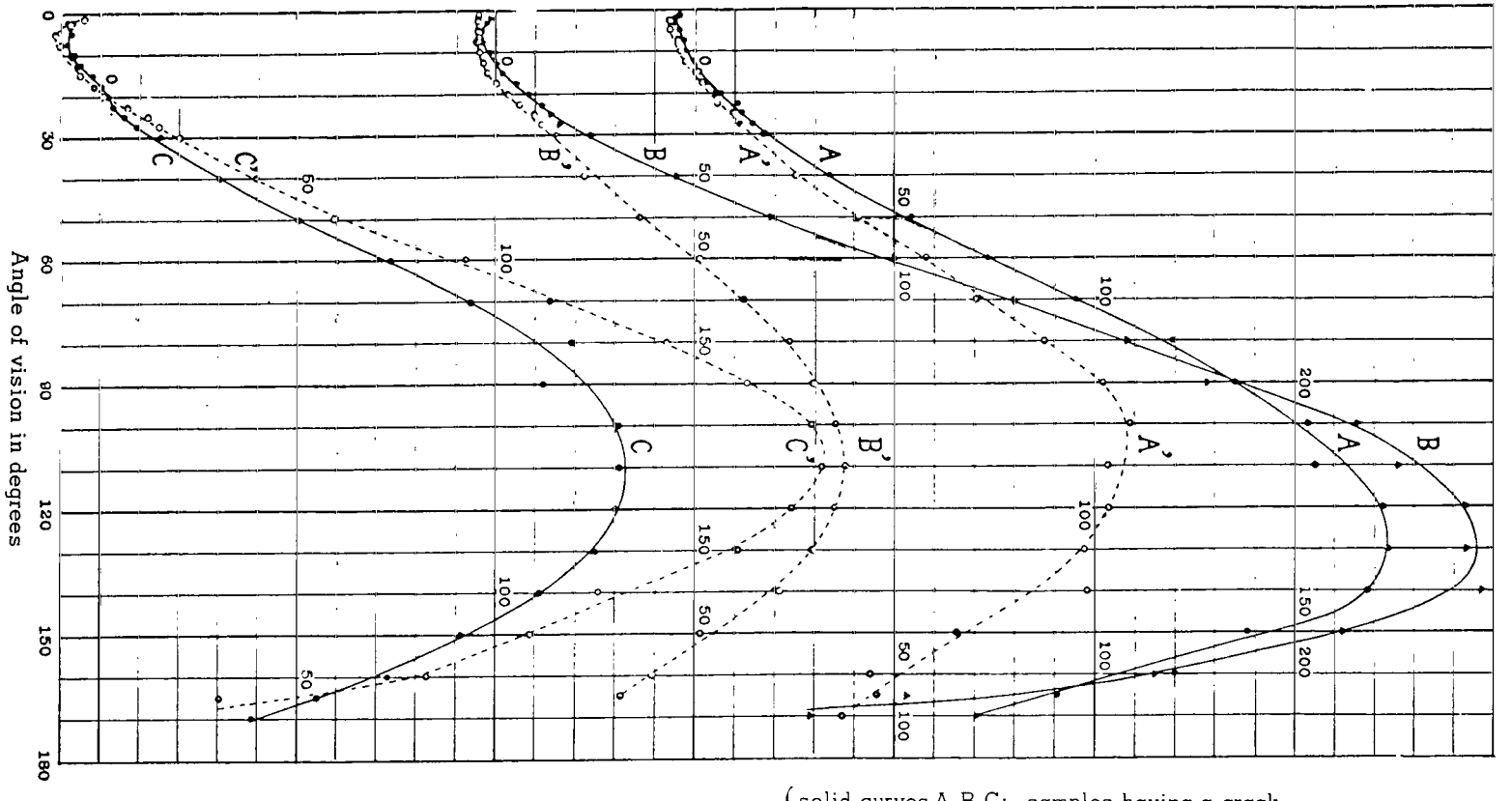


Figure 40. Mount Vesuvius Lavas, Symmetrically Observed { solid curves A B C: samples having a crack
dashed curves A' B' C': same samples, but powdered

H – Black lava, completely vitrified Albedo 0.029

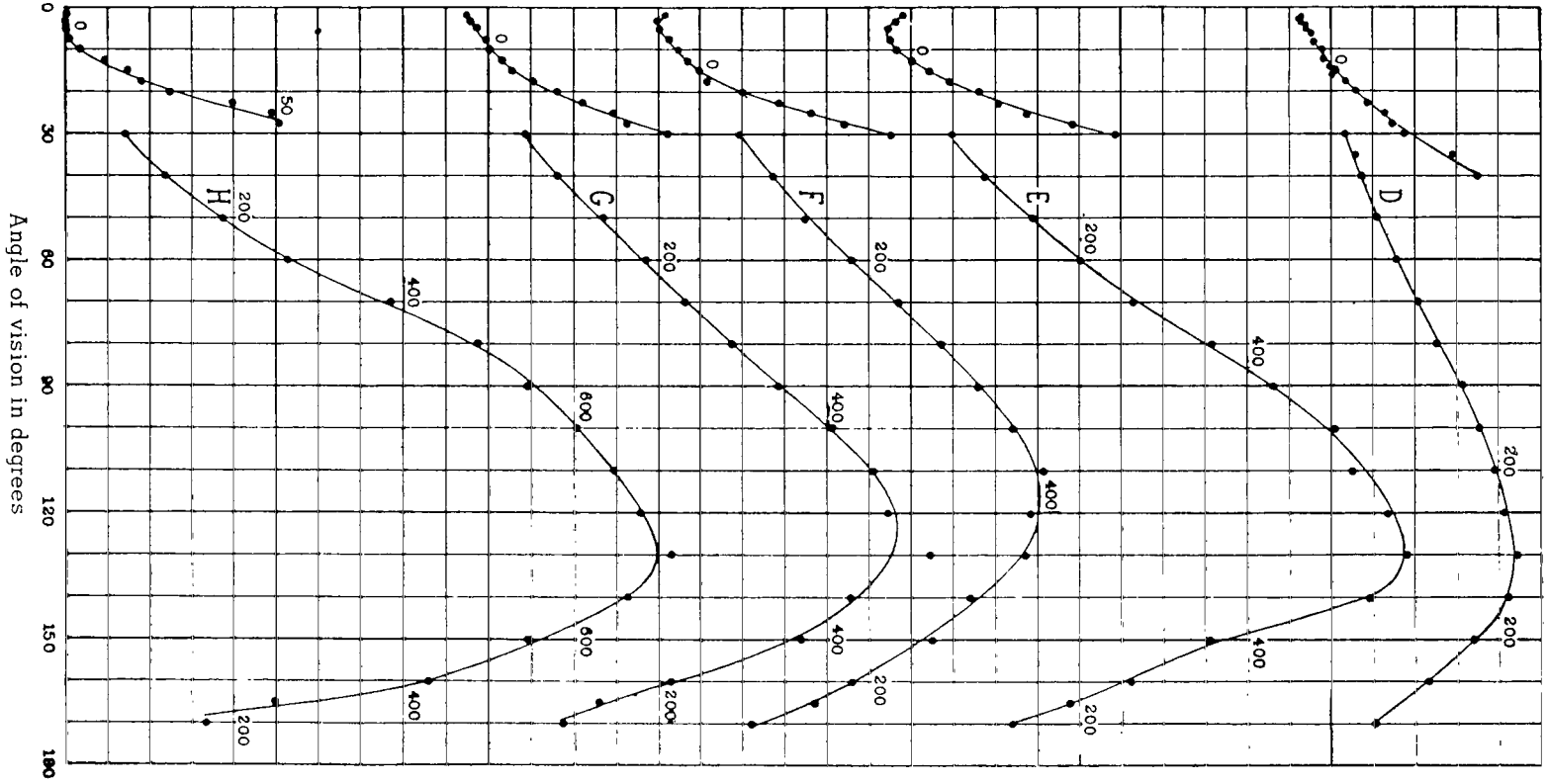
G – Black lava, shining Albedo 0.044

F – Black lava, porous Albedo 0.053

E – Black lava, transparent crystals Albedo 0.086

D – Gray lava, slightly porous Albedo 0.15

Ratio of polarized light – Scale: 1 division = 10 thousandths



Ratio of polarized light – Scale: 1 division = 50 thousandths

Figure 41. Lava Samples (Symmetrically Illuminated Crack)

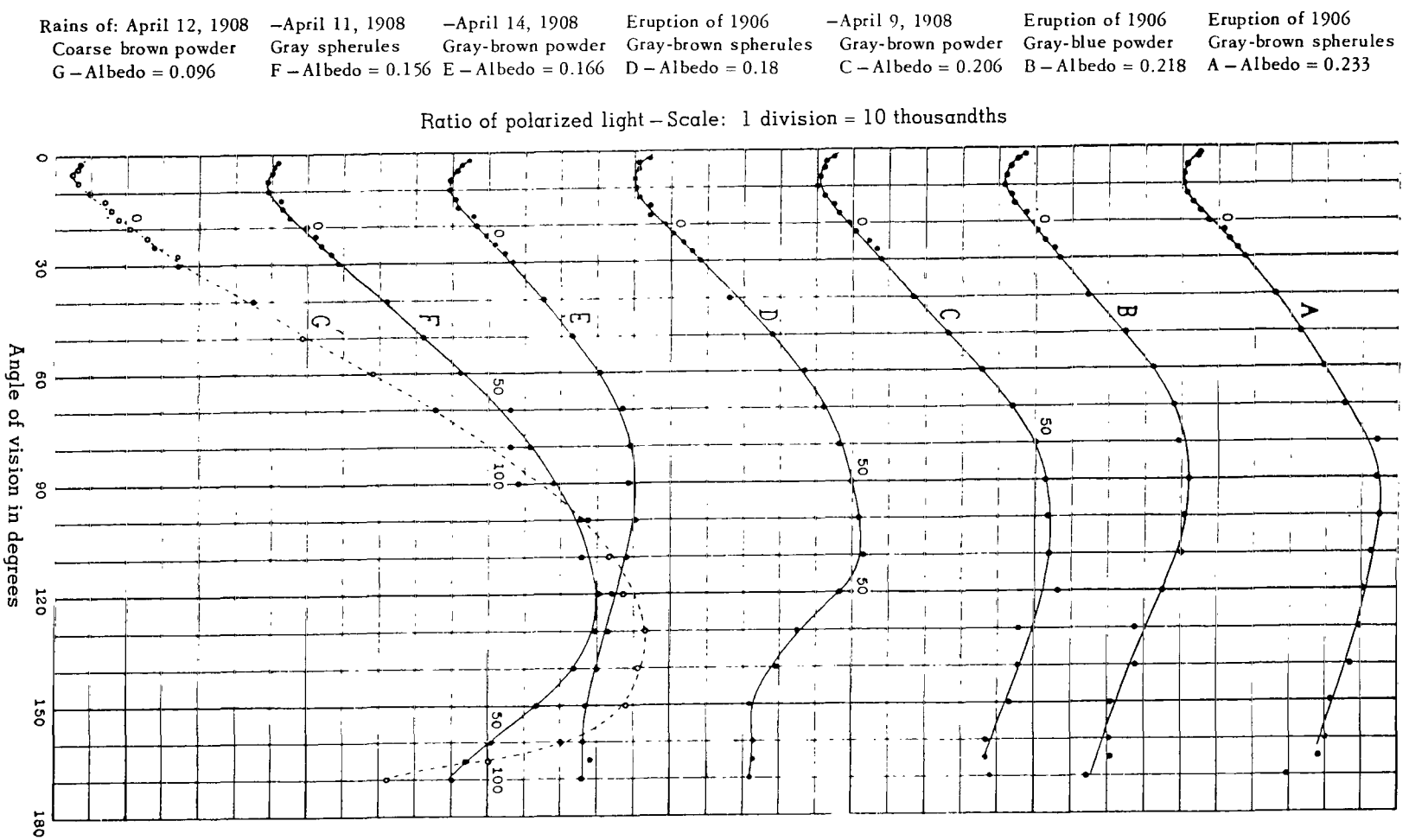


Figure 42. Mount Vesuvius Ashes

J – Rain of April 8, 1908
Gray grains, of 0.5 to 3 mm diameter
Albedo 0.048

I – Eruption of 1906
Black and brown grains, of 1 to 4 mm diameter
Albedo 0.051

H – Eruption of 1872
Black grains, of 0.3 to 1 mm diameter
Albedo 0.063

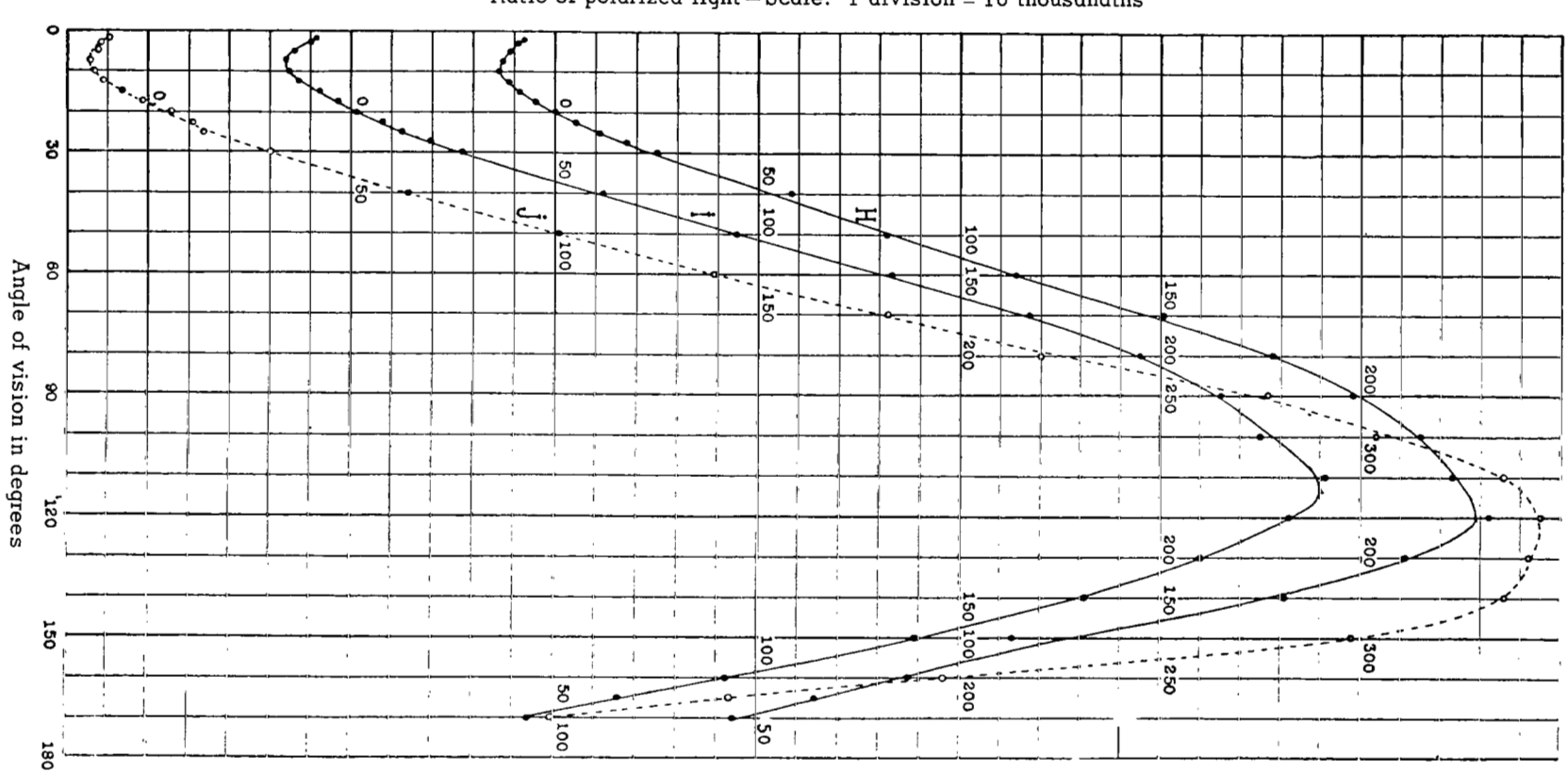


Figure 43. Mount Vesuvius Ashes

in a direction close to that of the source. This puzzling polarization seems to be attributed in some cases to the surface of the solid only, for example in the cases of cinnabar powder illuminated with blue light, and powdered galena. In the case of a substance with a medium albedo the negative polarization seems due in part to the light reflected by the surface, as demonstrated by the following experiment: the very porous sample of red lava (curve C, Fig. 42), when immersed in benzene, gives a negative polarization which is much weaker than in air, with a minimum of -5/1000 instead of -8 and an inversion angle of 10° instead of 17°. In the case of very white materials the negative polarization must come in greater part from the interior because the proportion of light reflected by the surface is very weak. These perplexing effects can seemingly be considered as consequences of the diffraction of light by particles composing the material. They seem to have similarity with the ones shown by the cloudy media, some examples of which will be studied at the end of this chapter. It is undoubtedly along this avenue that an explanation must be found for these effects.

Light Scattered in the Direction of the Source

A priori, we can expect to find in some cases an appreciable polarization for light scattered exactly in the direction of the light source. Take, for example, a white body having a vitrous surface and illuminated and examined at a very oblique incidence. The rays falling on this body will be polarized by refraction along a plane normal to the incidence plane. They will be scattered inside the body and greatly depolarized, but, coming back to the source they will undergo a new polarization of the same direction as the first one. In this way the inverted polarization found by Salet (1) on melted sandstone can be explained. I tried to determine whether the usual minerals have a similar effect to a lesser degree. It became difficult to examine the light of the material in a direction fairly close to that of the source (for the purpose of having a zero polarization by simple scattering). To do this I used the goniometer described previously, by placing the source very close to the polarimeter. The material is then moved in the direction of the goniometer so that the angle between the plane of vision and the goniometer is 45°, the angle of vision being 2°30'. The examined surface was either that of a powder or the roughly flat cut face of a mineral and it passed through the axis of the goniometer and could rotate with the latter. A pointer attached to the body gave the angle between the normal to its mean surface and the rays scattered toward the polarimeter. Under these conditions all the solid materials showed a visible polarization in a plane normal to the plane of incidence.

The ratio of polarized light increases with the angle of incidence almost as a parabola when the surface is fairly flat, and follows a more linear relationship when the surface is irregular. The reader should notice this by looking at the curves of Fig. 44 and at Table 15, the last column of which gives the ratio of polarized light deduced from similar graphs for an incidence of 80°. With this incidence the crystal powders gave polarizations from 2/ to 12/1000 which seemed to vary with the reciprocal of the grain birefringence. The polarization of the minerals varies strongly. It is very high for quartz sandstone, where it reaches 25/1000, 9 to 13 for the granites,

(1) SALET, Thesis, 1910, p. 58.

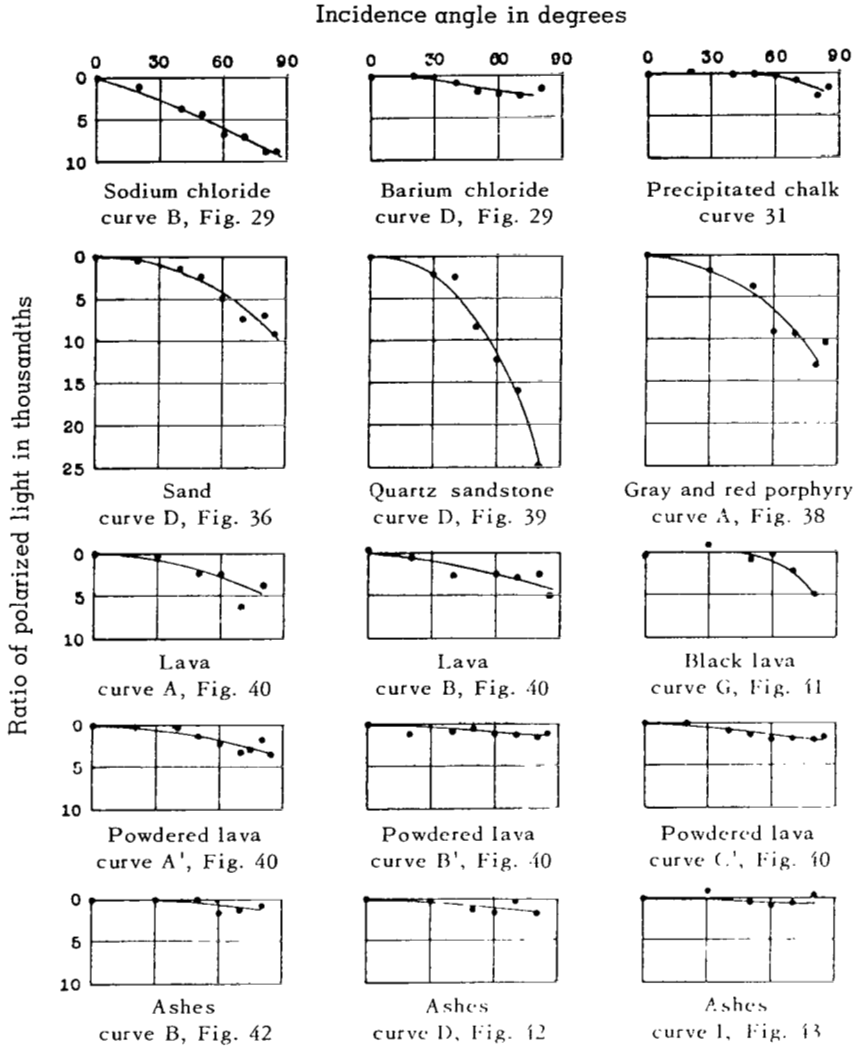


Figure 44. Solids—Polarization of Rays Scattered toward the Source

4 to 8 for the pieces of lava, and 1 to 3 for the powdered lavas, whereas for the volcanic ashes it was hardly noticeable and did not exceed 1/1000. For snow the polarization was about 12/1000, and variable with the state of fusion. Materials with partially reflecting surfaces yield very high values (100/1000 for Bristol board).

These effects seem to be due to a polarization by reflection, as mentioned before. Other materials have a similar appearance but their mechanism is quite different. Two examples of these follow. By using the polarimeter to study the light scattered by a grass plot illuminated by the Sun whose elevation was 28°, I noticed these facts. At 5', left and right of the shadow of the polarimeter, the polarization was horizontal and of 8/ to 9/1000. At the same distance above

TABLE 15
Polarization of Solids

	Curve	Albedo	Index	Vision Angle Inv.	Vision Angle Min.	Vision Angle Max.	Polarization Min.	Polarization Max.	C	R	P'×S	$\frac{R}{P'}$	R×S	$\frac{C}{P'}$	P
		S	N	I	∝	∝'	P	P'	C	R	P'×S	$\frac{R}{P'}$	R×S	$\frac{C}{P'}$	P
Homogeneous powders:															
Sodium nitrate	A fig. 29	0.71	1.58 / 1.33	....	.....	150°	0	+ 62	18	18	44	0.29	12	0.29	..
Sodium chloride	B 29	0.64	1.54	17°	< 3°	137	− 2	+ 34	1	74	22	2.18	47	0.03	9
Ammonium chloride	C 29	0.69	1.64	....	.....	145	0	65	9	106	45	1.68	73	0.14	..
Barium chloride	D 29	0.71	1.64 / 1.65 / 1.66	....	.....	> 160	− 2	100	25	44	71	0.44	31	0.26	2
Lead nitrate	E 29	0.79	1.78	....	.....	150	0	188	70	95	148	0.50	75	0.36	..
Precipitated chalk	31	0.82	1.49 / 1.66	....	.....	170	0	29	10	22	24	0.76	18	0.34	2
Powdered calcite	30	0.67	1.49 / 1.66	25	14	142	− 2	41	0	48	27	1.17	32	0	..
Magnesia	33	1.0	....	23	0.7	115	− 11	82	6	149	82	1.82	149	0.07	..
Cinnabar under red light	B 32	0.54	2.8 / 3.1	....	.....	157	0	66	21	55	31	0.83	30	0.32	..
Cinnabar under blue light	A 32	0.044	....	15	6	125	− 5	435	85	598	19	1.37	26	0.19	..
Crushed glass	A 33	0.76	1.52	....	.....	150	0	146	23	140	111	0.96	106	0.16	..
Glass spherules	B 33	0.50[1]	1.52	....	.....	140 / 18	0	152	35	170	76	3.09	235	0.23	..
Powdered magnetite	C 38	0.25	....	8	< 3	140	− 2	760	150	689	190	0.91	172	0.20	..
Powdered pyrite	D 38	0.15	....	....	.....	145	0	530	120	725	80	1.37	108	0.24	..
Powdered galena	E 38	0.11	....	22	11	140	13	570	110	630	63	1.10	69	0.19	..
Sedimentary rocks:															
Chalk	A 36	0.79	....	31	15	158	5	50	13	98	40	1.96	77	0.26	..
White clay	C 36	0.58	....	10	3	150	6	217	53	112	126	0.52	65	0.24	..

[1]Strongly variable albedo

TABLE 15 (Continued)

	Curve	Albedo Index		Vision Angle Inv.	Min.	Max.	Polarization Min.	Max.							
		S	N	I	α	α'	P	P'	C	R	P'×S	$\frac{R}{P'}$	R×S	$\frac{C}{P'}$	P
Grey clay	B fig. 36	0.17	....	15°	5°	120°	− 7.5	160	16	202	27	1.26	34	0.10	..
Sand	D 36	0.24	....	15	< 3	140	− 4	280	75	120	67	0.43	29	0.27	8
Igneous rocks:															
Grey & red porphyry	A 37	0.12	....	17	< 5	130	− 9	310	30	228	37	0.74	27	0.10	12
Blue-green porphyry	B 37	0.10	....	15	< 3	137	− 6	410	40	396	41	0.97	39	0.10	..
White & grey granite	B 39	0.14	....	13	< 3	130	− 4	170	30	127	24	0.75	18	0.18	8
Red sandstone	C 39	0.115	....	17.5	8	130	− 11	318	27	366	36	1.15	42	0.08	..
Quartzed sandstone	D 39	0.34	....	15	9	135	− 1	138	32	123	47	0.89	42	0.23	25
Basalt	A 39	0.079	....	13	< 3	120	− 3	223	27	355	18	1.59	28	0.12	1
Lavas:															
Grey, white crystals	A 40	0.23	....	13	< 3	128	− 5	173	12	277	40	1.61	64	0.07	5
Grey, porous	B 40	0.15	....	12	6	130	− 3.5	246	21	376	37	1.53	56	0.09	4
Red, very porous	C 40	0.082	....	17.5	7	110	− 8	132	11	338	11	2.56	28	0.08	..
Grey, slightly porous	D 41	0.15	....	14	< 3	130	− 7	220	20	297	33	1.35	45	0.09	..
Black, white crystals	E 41	0.086	....	12.5	6	130	− 5.5	580	70	506	50	0.87	43	0.12	7
Black, porous	F 41	0.053	....	15	4	117	− 10	400	25	506	21	1.26	27	0.06	..
Black, shining	G 41	0.044	....	9	< 3	125	− 5	480	60	486	21	1.01	21	0.12	5
Black, highly vitrified	H 41	0.029	....	....	.....	130	0	700	110	617	20	0.88	18	0.16	..
Powdered lavas:															
Grey, white crystals	A' 40	0.17	....	16	3	105	− 7	108	7	242	18.4	2.24	41	0.06	3
Grey, porous	B' 40	0.17	....	17	5	110	− 5	88	3	262	15	2.98	45	0.03	1
Red, very porous	C' 10	0.15	....	19	6	108	− 11	182	11	372	27	2.05	56	0.06	1
Volcanic ashes:															
Grey-brown spherules	A 12	0.233	....	22	9	95	− 9	45	*	229	10.5	5.09	53	*	..
Fine grey-blue powder	B 12	0.218	....	22	10	90	− 8	42	0	198	9	4.72	43	0	1
Fine grey-brown powder	C 12	0.206	....	22	9	105	− 9	54	0	230	11.2	4.27	47	0	..
Medium grey-brown powder	.....	0.191	....	22.5	8	103	− 10	43	*	223	8.2	5.18	43	*	..
Fine grey-brown powder	.....	0.185	....	20	7	98	− 7.5	49	*	222	9.1	4.53	41	*	..

TABLE 15 (Continued)

	Curve	Albedo	Index	Vision Angle Inv.	Min.	Max.	Polarization Min.	Max.							
		S	N	I	∝	∝'	P	P'	C	R	P'×S	*R/P'	R×S	*C/P'	P
Grey-brown spherules ...	D fig. 42	0.180	....	22°	8°	108°	− 10	53	*	215	9.6	4.07	39	*	1
Fine grey-brown powder..	E 42	0.166	....	23	9	93	− 11	40	*	211	6.6	5.28	35	*	..
Fine grey powder	.....	0.162	....	21.5	9	101	− 9	58	*	252	9.4	4.35	41	*	..
Grey spherules	F 42	0.156	....	21	8	122	− 11	80	0	273	12.5	3.42	43	0	..
Coarse brown powder....	G 42	0.096	....	19	6	132	− 15	93	2	334	8.9	3.59	32	0.02	..
Grey, 0.6 mm grains.....	H 43	0.063	....	20	10	120	− 13.5	228	8	390	14.3	1.72	25	0.04	..
Grey, 0.2 mm grains.....	.....	0.059	....	19	10	127	− 12	267	12	432	15.8	1.62	25	0.05	..
Black and white, 0.6 mm grains.....	.....	0.058	....	17.5	8	120	− 14	310	11	434	18.1	1.40	25	0.04	..
Black and brown, 2 mm grains.....	I 43	0.051	....	19	9	112	− 16	140	10	462	7.2	3.30	23	0.07	..
Black, 0.5 to 3 mm grains	J 43	0.048	....	18	8	120	− 14	345	20	443	16.5	1.28	21	0.06	..

S: Albedo with the definition given on (French) page 112.

I: Inversion angle
∝: Abscissa of the minimum
∝': Abscissa of the maximum
} in degrees.

P: Minimum ratio of polarized light
P': Maximum ratio of polarized light
} in thousandths.

C: Concavity defined by the maximum difference of ordinates between the curve and a tangent drawn to the curve, either from the inversion point, or from the point where it leaves the abscissas axis. When the curve is convex towards the negative ordinates, the numbers are replaced by an asterisk.

R: Ratio of residual polarized light, expressed in thousandths, as obtained from a completely polarized incidence light measured in the direction of the source.

P: Ratio of light polarized in the direction of the source, with natural incident light: angle of incidence: 80°.

*(The original indicates $\frac{P'}{R}$ and $\frac{P'}{C}$, obviously in error. Translator's note).

the shadow the polarization was still horizontal, but much higher; i.e., 17/1000. The measurements repeated on the various points of the grass plot gave similar results. We can conclude that the grass, for an angle of vision of 5°, gave a negative polarization of 4.5/1000 which was added to a horizontal polarization of 13/1000. These effects could only be due to the polarization of the general light of the sky because the latter was much less intense than the light from the Sun, and the polarization it produced in the shadow of the polarimeter was less than 14/1000. In this case the polarization which is observed in the direction of the source can be attributed to the light undergoing multiple scattering or several successive reflections on the grass blades and being strongly polarized normally to the direction of the blades.

A pine board, illuminated and examined face-on, polarized the light in a plane perpendicular to the wood fibers. The same was true of a galena crystal whose break was at an angle with respect to the plane of cleavage. Its surface was coarse, with grains whose edges generally had a common orientation. The scattered light was polarized normally to this orientation.

Study of Cloudy Media—Transparent Clouds of Water Droplets

Influence of the Drop Diameter

Since clouds of water droplets are very common in nature it is important to know their polarization. On this subject we have some valuable indications given by the observations of Soret and by the calculations of Shoulejkin, but these indications apply only to a very small number of special cases and are not sufficiently accurate. The polarization is so dependent on the drop diameter and on the cloud transparency that it is necessary to study several examples experimentally.

Large Drops

First I studied the polarization of a water drop measuring approximately 1.5 mm in diameter. This drop was produced by a glass tube filled with water and having a carefully greased tapered end (1). The other end was plugged by a cork pierced with a machine screw. When the screw is turned, a small quantity of water comes out of the capillary end. Since the water does not adhere to the glass it takes the shape of a sphere, and it was easy to adjust its diameter and compensate the evaporation with the screw. The drop was suspended at the center of the goniometer and its image was formed at the center of the polarimeter eyecup, into the pupil of the observer who in this way received all the light from the drop.

In this way I obtained the curve A of Fig. 46. It is easy to explain its shape by examining the successive aspects presented by the drop when observed in the various directions taken by the polarimeter. These aspects are schematically shown at the bottom of the figure. The drop always appears completely dark, except in certain points aligned along a diameter passing through

(1) This process was mentioned by WOOD: Optique Physique, Vol. 1, p. 421.

the source; these are images of the source. Their lights are polarized in a plane which is either parallel or normal to the plane of vision. Their intensities and their ratios of polarized light vary greatly with the direction of observation.

The total light scattered by the drop can be considered as the mixture of the lights from these different images. It is necessary to consider the most intense images which are produced by the ray A, Fig. 45, reflected inside the drop; the ray D, refracted twice; the two rays B and B' reflected once inside the drop and refracted twice, and finally the rays C and C' reflected twice inside and refracted twice. The other rays--theoretically an infinite number of them - are much weaker and can be neglected in all directions. Fig. 45 shows that the images given by the rays A, C and C' must appear on the same side as the source, whereas those given by the rays B, B' and D appear on the opposite side. All except D are polarized along the plane of vision. When the angle of vision is small the only images are A and B situated near the center. Their polarization is nil at first. The polarization of A increases slowly, that of B much faster. Around 15° the image B' appears highly polarized at the edge opposite the source. B and B' approach each other and their intensities increase greatly. This is why the polarization of the drop increases more and more rapidly. Around 40°, B and B' are coincident and give rise, in the direction of the primary rainbow, to a light spot which is extremely intense and disappears later for 44°. These effects show up on the curve as a first sharp maximum followed by a sudden drop down to the value given by Fresnel's formulas for the image A. Later, at approximately 48°, the image C appears, soon becomes very intense, then at 55° is split into two images C and C' which rapidly weaken and disappear. These changes appear with the secondary rainbow, and show up as a second sharp maximum. The polarization of the drop, reduced to that of A, then increases very rapidly. Around 100° the image D appears and soon becomes very intense. Since D is negatively polarized, the curve drops with a high slope and changes sign; then, since the polarization of D decreases, the curve tends to the x axis, which it meets at approximately 180°. These effects are much more complicated than those theoretically predicted by Shoulejkin (1). Incidentally, for his calculations he took into consideration only the A and B rays.

Drops of Approximately 300μ

I studied finer droplets produced by very fine water jets from a pencil of capillary tubes. The obtained curve is not shown here. It is close to the preceding one, but shows certain distortions due to diffraction. The inversion angle decreased from 112° to 110°, whereas a small positive branch appeared for the great angles, with a new inversion point b for 168°.

Drops of Approximately 35μ

These drops were produced by a vaporizer fed by the flow of air at constant pressure from a water bulb. They yielded the curve B of Fig. 46. At 105° the inversion point is found again, but

(1) SHOULEJKIN, Scattering of Light by Large Colloidal Particles, Philosophical Magazine, Vol. 48, 1924, pp. 307 to 320.

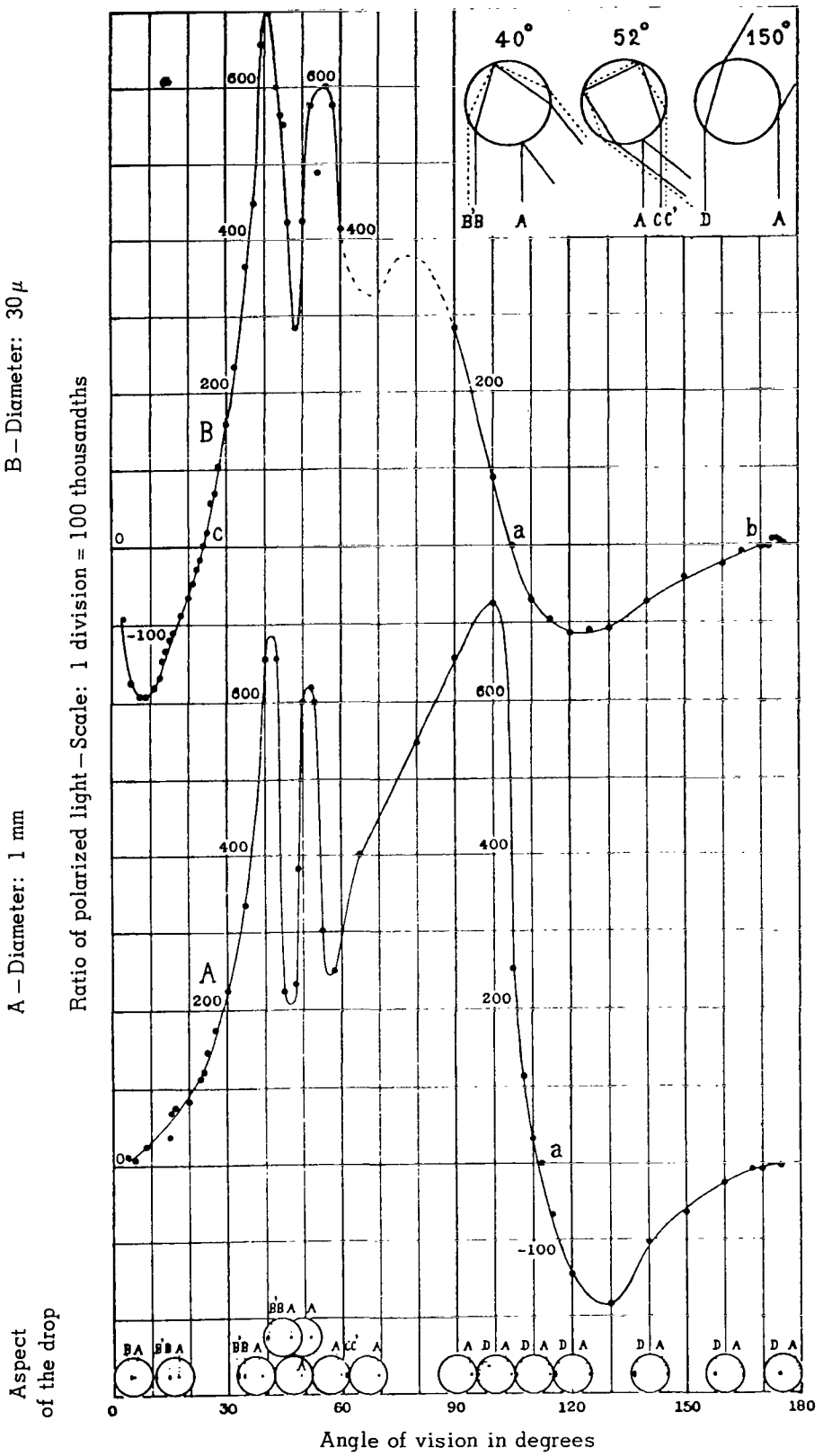


Figure 45. Principal Rays

Figure 46. Water Droplets

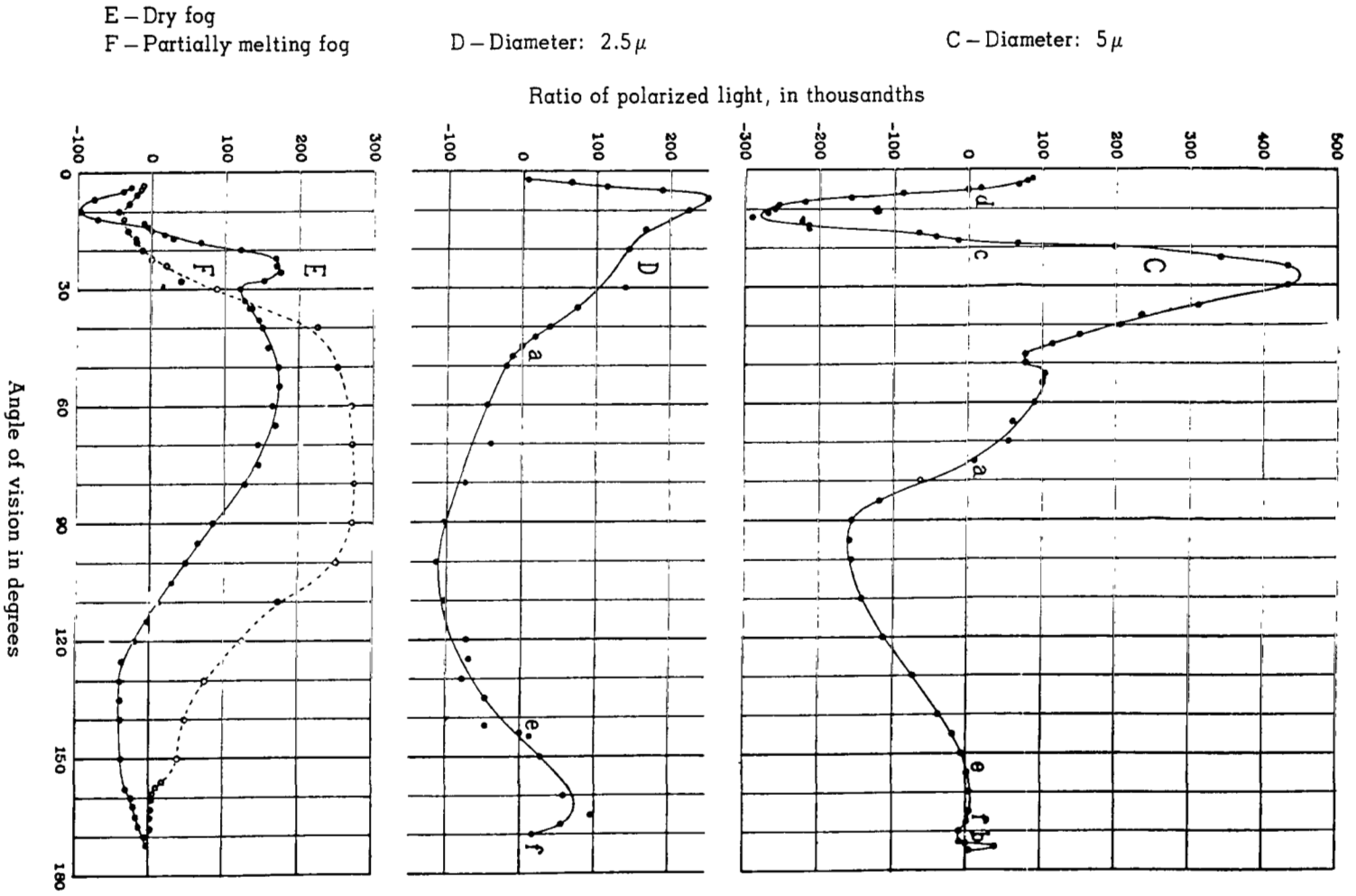


Figure 48. Ice Fog

Figure 47. Water Droplets

again displaced toward the small angles. The second inversion point b is moved to 173°. A third inversion point c appears around 24° preceded by a sizeable negative branch.

Droplets of about 5μ

The curve C of Fig. 47 is obtained from droplets produced by the condensation in air of a water vapor jet. The droplets formed a transparent cloud through which the source appeared surrounded by a halo of 3.5° radius (this allowed the calculation of a radius close to 5μ for the droplets). On this curve we see the diffraction effects becoming more and more important. The principal angle of inversion fell to 76° (1), the angle c also decreased, whereas another inversion point appeared at d. The point b is found at 173° preceded by two new inversions e and f, with a hump around 160°. As a consequence the diffraction has a large drop of the maximum of the secondary rainbow and an increase of that of the primary one.

Very Fine Droplets

To study still finer droplets I placed at the center of the goniometer an almost spherical glass flask of one liter capacity, whose walls had been previously carefully cleaned of dust, so as to scatter the least amount of light possible. This flask contained some water and was filled with air saturated with vapor. By expanding this air with a rubber bulb one could see the spherical flask filled with a fog of very fine droplets through which the source appeared surrounded by a light spot and by concentric rings having a series of interfering colors. The diameters of these halos decreased when the air expansion increased. I adjusted the expansion so that the central spot had the green color of the first order. The diameter of the drops as evaluated from this color seemed to be close to 2.3μ. The central spot, more brilliant than the rings, had an apparent diameter of about 15°. By regarding it as a halo we find a diameter of 2.2μ for the drop. This diameter must have been approximately the same for all the drops because of the purity of the colors obtained.

The fog condensed rapidly so that it was necessary to perform several expansions for each measurement. I checked the constancy of the drop diameters from the colors. In spite of this I could not avoid having small discrepancies, and this is why the points for the obtained curve (curve D, Fig. 47) are more dispersed than for the preceding curve. The curve has a principal inversion angle a which is smaller (only 45°). The point d has disappeared, and b and c could not

(1) The most frequent terrestrial clouds are made of droplets slightly thicker than these, as shown by the halos they form when passing before the Moon (these halos have a diameter of 1 to 2°). The same must be true of the clouds Soret observed in the mountains. This physicist found, almost as I did, a negative branch between 3° and 20°, a positive maximum around 40°, an inversion around 90° and a negative maximum around 135° (see French page 97). The opaqueness of the cloud was then total and did not seem to have drastically modified the positions of the maxima and of the inversion points.

be observed, whereas e and f are more separated. The positive branch has greatly decreased and the points corresponding to the two rainbows have completely disappeared.

Transparent Ice Fogs

I used the following procedure to study ice fogs. A small fan sends a slow flow of air into a Dewar tube, containing liquid air, through a rubber hose whose orifice is slightly above the surface of the liquid. A clamp allows the flow of air to be regulated. In the course of experiments the temperature of this air was of +16° C and its dew point was about +5° C. Its mixture with the cold air coming from the liquid produced condensation in the form of a cloud of fine crystals sparkling under the light. I studied this cloud at the mouth of the Dewar tube which was placed near the center of the goniometer. The polarization of the light scattered by the cloud varied with the rate of air flow. With a very small rate I obtained the curve E of Fig. 48. By progressively increasing the rate the curve changed its shape and rapidly approached the curve F. The curve E seems to be due to partially melted crystals, and has features which are common to the curve C obtained for the water droplets of about 5μ diameter (same abscissa for the first minimum and for the two maxima; negative polarization at large angles). The curve F resembles that of volcanic ashes but with a much stronger negative polarization for the small angles and a smaller abscissa for the maximum. Around 156° the curve undergoes a few oscillations, undoubtedly due to diffraction, and the same happens at the initial negative branch. We could have expected a sudden drop of light at approximately 157°, accompanied by an increase in the polarization, corresponding to the passage of the observer into the 22° halo (1). Nothing like this was observed. As a matter of fact, this halo remained invisible; undoubtedly because of the considerable diffraction effects resulting from the fineness of the crystals. The size of these crystals must exert a preponderant influence upon the shape of the polarization curve. It would therefore be very important to pursue these measurements with clouds formed from crystals having as many different sizes as possible.

Opaque Droplet Clouds

Influence of the Thickness

Nature rarely offers us clouds as transparent as those we have just studied. As Soret noticed, the case of an opaque cloud is fairly different; each drop receives light not only from the source but also from the neighboring drops. Since every drop scatters a light whose intensity and state of polarization varies tremendously depending on the direction, it would be very difficult to calculate the corresponding polarization curve. It can be predicted however, that the polarization of a very extended cloudy layer, uniformly illuminated on all its surfaces, must not depend on the distance between the drops, because this distance is always great with respect to their diameter. The polarization must only be a function of the opaqueness of the layer.

(1) Translator's note: Within the cone whose angle is 22° with respect to the 180° direction.

I tried to solve the problem experimentally with the help of the following arrangement. A colloidal solution of spherical transparent grains suspended in water, is contained in the bottom hemisphere of a spherical glass flask of one half-liter capacity. The top hemisphere of this flask is filled with ether. The grain substance is soluble in ether and this prevents these grains from sticking to the surface separating the two liquids. The spherical flask is placed at the center of the goniometer and the pencil of light from the source is enlarged so as to illuminate the surface of the grain clouds almost completely, while the polarimeter is pointed on the central part.

With a very opaque colloidal solution the conditions are equivalent to those of a thick cloud of infinite dimensions illuminated by the Sun and examined by an observer located above the surface of this cloud. The ray reflected on the surface of separation of the two liquids was eliminated by having an angle of incidence greater than the angle between the normal and the direction of the polarimeter. The angles of vision were calculated by considering the refraction produced through the separation between the two liquids which was always less than 4°. This refraction introduced errors less than 1/1000 in the polarization measurements. Actually, it would have been easy to separate this refraction by dissolving a substance into the water which would make its index equal to that of the ether.

By this process I tried to study colloidal solutions formed by spherical grains having an index with respect to water approaching as much as possible 1.33, the index of water with respect to air. These solutions were prepared by dissolving the substances in alcohol and pouring the solutions into a large quantity of water. Diodomethane, index 1.737, which lost its color by contact with mercury, did not give a solution stable enough to permit the measurements. The same behavior was observed for carbon sulfide. A fairly stable solution was obtained, however, with bromonaphthalene. Examined under a microscope the solution showed itself to be formed by grains of various sizes. The most numerous had a diameter of about 2μ. The solution, when placed before a source of light, in a vessel having parallel walls gave a hazy halo of about 11° radius. The curve B, Fig. 49, was obtained with this sufficiently concentrated solution so as to completely scatter the light within a thickness of 1 cm. The curve A is obtained with the same solution diluted so as to scatter only a few hundredths of the incident light. They both have almost the same shape. The multiple scattering has as principal effect a decrease in the polarization, which on the average is three and one half times smaller in the case of B. In addition the ordinates seem to be slightly less reduced for the great angles than for the small ones, which is natural since the grains scatter more light opposite the source than toward the source. For this reason we can even predict that the multiple scattering must in certain cases decrease the principal inversion angle which in this case is 120°. In fact the rays which arrive at the polarimeter at 120° from the source after having been scattered only once are not polarized. Those which undergo two scatterings at angles of the order of 150° are negatively polarized and since the grains at this angle send a large amount of light their polarization can be dominant, and this has the effect of shrinking the curve and of decreasing the inversion angle. This effect must be considerable since an isolated drop scatters more negatively polarized light and also less positively polarized light.

I have repeated these experiments with a colloidal solution of synthetic resin, index 1.63, obtained by precipitation of its solution in alcohol. The grains formed were very small. Most of

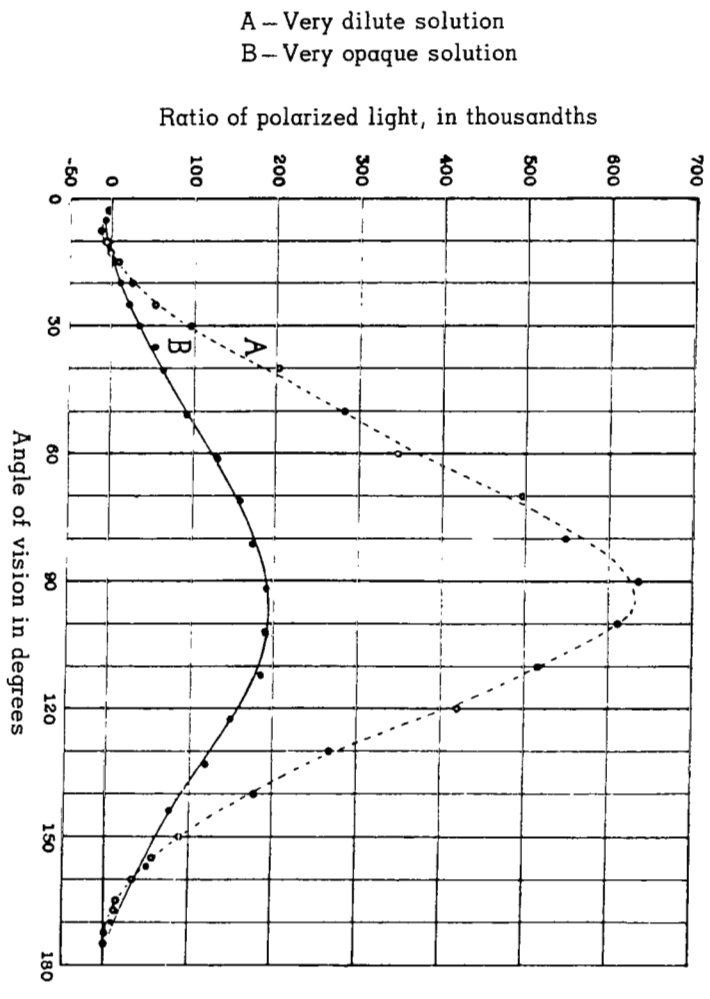


Figure 50. Colloidal Solution of Resin in Water

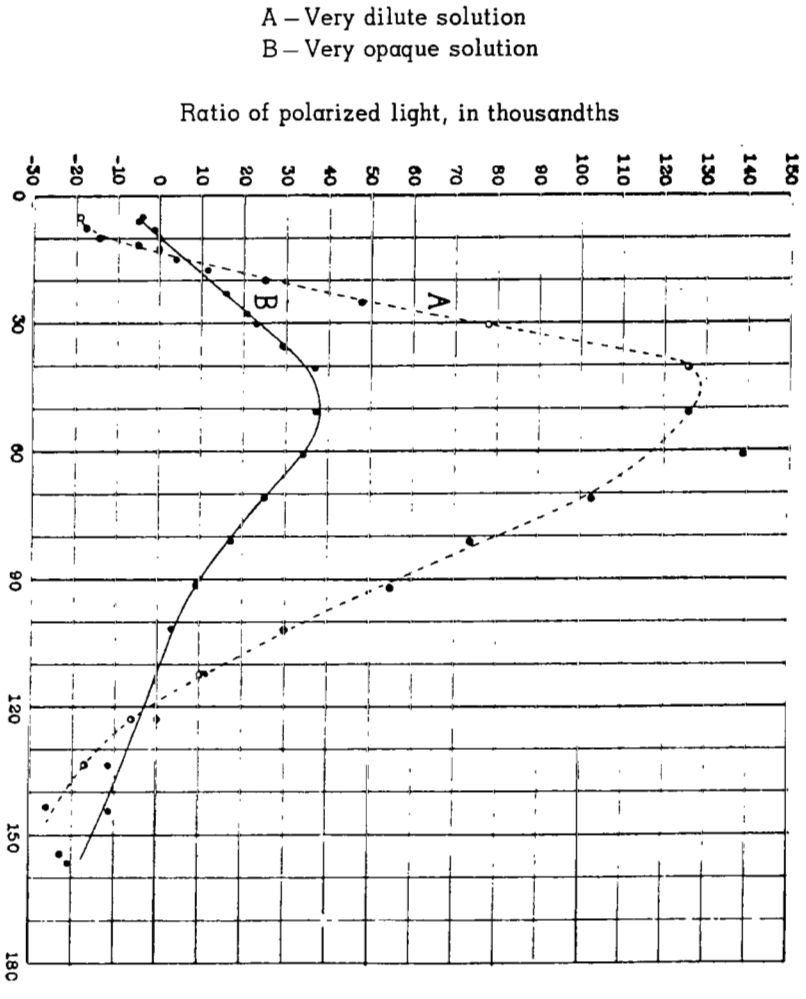


Figure 49. Bromonaphthalene Emulsion in Water

them did not have a detectable apparent diameter when observed through a microscope equipped with an immersion type objective. The fairly diluted solution seemed red by transmission and scattered a blue light. The curves B and A of Fig. 50 show the results obtained with this solution, first very concentrated, then diluted. They have the same shape and their ordinates are approximately in the ratio of 1 to 4.

It would be interesting to pursue these experiments with a colloidal solution of grains having a relative index close to 1.33 with respect to water. Perhaps these grains can be formed with a solution of phosphorus into bromonaphthalene or even into a resin. In this way the case equivalent to various aqueous clouds could be studied.

PART THREE–ATTEMPTS TO INTERPRET THE PHENOMENA OBSERVED ON THE PLANETS

Introduction

The study of terrestrial substances which was described in the preceding chapter will allow us to explain a few of the results obtained for the planets, although this study of the substances is still quite incomplete. In the course of this last chapter we shall attempt to determine for each planet the nature of its ground when it is directly available to view, and whether its clouds cover a few regions or hide the ground completely. Finally we shall try to evaluate, whenever possible, the thickness of the atmosphere situated above the visible surface, ground or clouds, with the aid of the acquired results.

In contrast to Part One and Part Two which illustrate facts, Part Three will contain a certain number of assumptions which are necessary because of the inadequacy of our knowledge concerning the polarizations produced by the various materials. As the reader will notice, some of the conclusions which we have to draw are nevertheless very probable. Others are only notes which I thought required mention because they indicate which avenues future research must take. These are work hypotheses.

CHAPTER VII. THE MOON

Ground

Numerous observations, and in particular those of star occultations, have shown that our satellite is not surrounded by any detectable atmosphere. The polarization measured is therefore due to the ground. By comparing the Moon curve with the curves obtained for the various substances, it is found that the Moon curve shows a few properties which are common to most absorbing materials, namely, negative polarization for the small angles of vision, then minimum, then a change of sign and advance to a positive maximum for an angle greater than 90°. The Moon curve differs however from those of the most abundant Earth minerals by the following properties:

1. The inversion angle is greater.

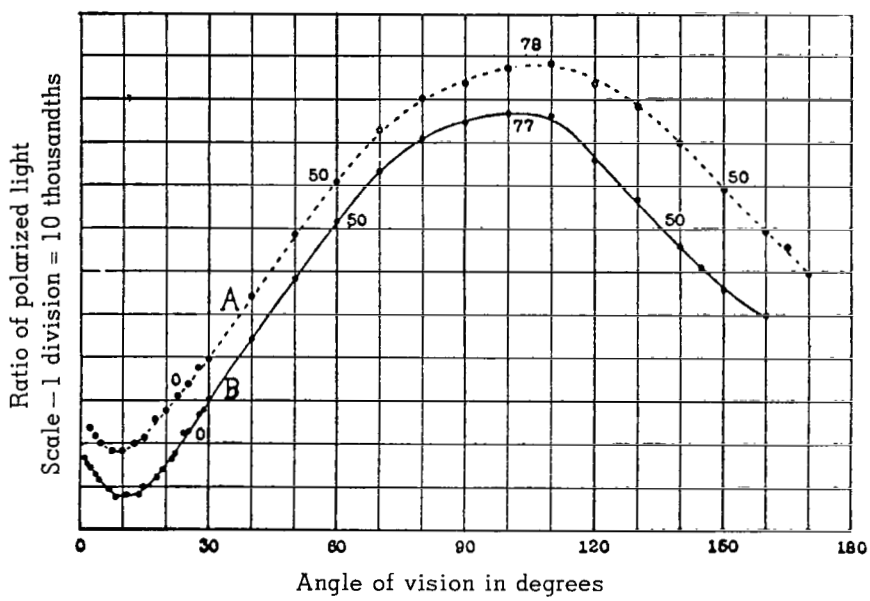
2. The negative polarization is higher, whereas the positive polarization is weaker.

3. The minimum is reached for a greater angle of vision and the maximum for a smaller angle.

Of all the studied substances only volcanic ashes have a set of properties close to the ones listed above. Let us compare these properties to those of the various regions of our satellite. The ashes are grey, with hues which are sometimes brown, sometimes bluish, and these hues resemble, but in a more intense way, the weaker colors which are seen on the lunar seas (with the help of the refractor equipped with a very bright eyepiece). Their albedo, defined as the brightness ratio with the brightness of a perfectly scattering white body, ranges from 0.48 to 0.233 in the direction of their source. These figures are of the same order of magnitude as those of the darkest and clearest regions of the Moon. The curves for the ashes have a shape which varies regularly as a function of the albedo, but the variations are more pronounced than for the Moon. From the darkest to the clearest regions the following is observed.

The inversion angle increases for the ashes from 18° to 23°, and for the Moon from 22°40' to 23°35'. The minimum changes for the ashes from -16/ to 9/1000, and from - 12.5/ to -9/1000 for the Moon. The maximum decreases for the ashes from +340/ to +40/1000, and from +200/ to +48/1000 for the Moon. The abscissa for the maximum for ashes is between 8° to 10°; for the Moon it is 10°.

The curve A of Fig. 51 represents the ratio of polarized light of a surface covered in part by fine grey-brown ashes of 0.166 albedo (curve E, Fig. 42), and in part by other ashes composed of black-brown grains of 0.051 albedo (curve I, Fig. 43). The ratio of the areas, covered by the first and by the second types of ashes was taken equal to 1.52, in order that the maximum polarization for the mixture be close to that of the Moon. Under these conditions the average albedo for the



A – Mixture of ashes, of 0.13 albedo
B – Average curve for the Moon

Figure 51. Lunar Ground and Volcanic Ashes

area is 0.13. This number represents fairly well the average albedo of the Moon according to the definition employed in the present work (1).

The curve B of Fig. 51 is the average of the curves for the first quarter and the last quarter of the Moon. The similarity between the curves A and B is remarkable, considering the great differences that the curves of other materials show. On the other hand, the volcanic ashes scatter back in the direction of the source, even for very high angles of incidence, a proportion of polarized light which is smaller than that of all the other substances studied. This proportion never exceeds the ratio of 1/1000. I have shown (French page 46) however, that the Moon shows this effect only very faintly. Finally, the lunar ground, when obliquely illuminated, scatters much more light in the direction close to the Sun than in the opposite direction. The same is true of an area covered with dull powders and especially with volcanic ashes. All these similarities lead us to conclude that the Moon must be almost completely covered with powders having a constitution similar to that of the Earth's volcanic ashes. These powders could also be in the form of a very

(1) The value of this quantity is poorly known. Zöllner gave the value of 0.17, the Annuaire du Bureau des Longitudes gives the value of 0.15, the work entitled Astronomy by Russel, Dugan and Stewart gives for the most probable average value for the brightness of the full Moon a value of 1/465,000 with respect to the Sun (from this ratio a value of 0.110 is found for the albedo).

thin layer. But the polarizations which I found agree poorly with the current opinion that the lunar ground surface which is available to our view is formed by volcanic lavas (1).

Mercury

Ground

I have not yet been able to determine the complete curve for Mercury. The known part of the curve is very close to the average of the two lunar curves, which are supposed to be drawn by considering the relative brightnesses of the first and last quarters. The polarization of Mercury is lower than that of the Moon by less than 4/1000, i.e., it is 1/20 of its value. On the other hand, the albedo of this planet is close to that of our satellite. It is therefore very probable that the ground of Mercury has the same constitution as that of the Moon. Müller arrived at the same conclusion by a very different method. He wrote (2): "The curves of the light of Mercury and of the Moon agree surprisingly well between the phase interval from 50° to close to 180°," to the point of giving "to the surface of Mercury a nature quite similar to that of the Moon." From the work entitled Astronomy (3) the increase in brightness at the full Moon is slightly more pronounced for Mercury than for the Moon.

Atmosphere

The measurements of the polarization allow us to assume an upper boundary to the thickness of the atmosphere of Mercury. Indeed, assume for a moment that the coincidence between the curve of the planet and that of the Moon is purely accidental—this is highly unlikely—and that the polarizations observed on Mercury are due in part to its ground and in part to a transparent atmosphere. Around dichotomy let P be the apparent ratio of polarized light for Mercury, I_1 and P_1 the brightness and the ratio of polarized light from its ground (observed through the planet's atmosphere assumed not to be illuminated), I_2 and P_2 the brightness and the ratio of polarized light of its atmosphere. We have approximately

$$P = \frac{P_1 I_1 + P_2 I_2}{I_1 + I_2}$$

from which we get

$$\frac{I_2}{I_1} = \frac{P - P_1}{P_2 - P} \qquad \text{and} \qquad (8)\ \frac{I_2}{I_1 + I_2} = \frac{P - P_1}{P_2 - P_1}.$$

Let us find out what the maximum value of this ratio can be. The albedo of Mercury as measured around full phase is close to 0.16 (4). That of the ground can only be equal to or smaller than

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(1) BARABASCHEFF, Astronomische Nachrichten, Vol. 229, No. 5473, p. 7, 4 September 1926.
(2) MÜLLER, Astronomische Nachrichten, 1893, No. 3171.
(3) RUSSEL, DUGAN and STEWART, 1927.
(4) L'Annuaire du Bureau des Longitudes gives the value 0.16 and Russel gives the value 0.164.

this value. All the substances studied in the laboratory which have such a dark hue have maximum polarizations greater than 40/1000. The various regions of the lunar ground behave likewise. The maximum polarization P_1 of the surface of Mercury is probably not less than this value. Assume therefore that the value is 40/1000, or 0.04. At first quarter the light scattered by the atmosphere of the planet must be highly polarized because of the weak brightness of its ground. Take the value 0.9 for the ratio of polarized light. The apparent polarization P of Mercury as measured around the first quarter is equal to 0.073. With these figures formula 8 gives for the brightness of the atmosphere with respect to that of the planet the value

$$\frac{0.073 - 0.04}{0.9 - 0.04} = 0.038$$

Assume that this atmosphere is made of pure and dry air and has absolutely no dusts. The formula of Lord Rayleigh, applied to the case of anisotropic molecules and verified by several methods by Cabannes (1), allows us to calculate the light intensity of a cubic centimeter of air. Let J be the light intensity with respect to the incident rays of 1 cc of air at 0° and 760 mm Hg, illuminated by parallel light. Let ϕ be the light flux received by the air, λ the wavelength of the light, n the refractive index of air, m the number of molecules per cubic centimeter, ρ the intensity ratio of the components of the scattered light vibrating parallel and normal, respectively, to the incident rays. The formula gives

$$\frac{J}{\varphi} = \frac{\pi^2(n^2 - 1)^2}{2m\lambda^4} \cdot \frac{6 + 6\rho}{6 - 7\rho}.$$

Taking

$$\lambda = 0.55 \cdot 10^{-4}$$

We have

$$n = 0.000\,2926$$

and

$$m = \frac{65 \cdot 10^{22}}{22\,500} = 2.9 \cdot 10^{19}.$$

The measurements of Cabannes give $\rho = 0.04$ from which we get

$$\frac{J}{\varphi} = 7.15 \cdot 10^{-9}.$$

Let B be the brightness of a white and perfectly scattering screen, normal to the rays illuminating the gas. We have $\phi = \pi B$. The brightness of an air layer 1 cm thick which is examined normally is therefore $7.15 \times 10^{-9} \times \pi = 2.25 \times 10^{-8}$ times that of the screen. The average brightness of Mercury at the full phase referred to that of a similar screen is approximately 0.16 (Zöllner's albedo). It decreases more sharply than Lambert's law predicts. At dichotomy, according to this

(1) CABANNES, Journal de physique, November 1920.

law, this brightness should be reduced to one third that value. The brightness measurements lead to 1/8. The average brightness of Mercury at the first quarter is therefore:

$$\frac{0.16}{8} = 2 \cdot 10^{-2}.$$

The average brightness of its atmosphere does not exceed 38/100 this value, as we have seen before. Around the center of the planet, where the gas layer is normal, its brightness is still half as much. At most, the value is $2 \times 10^{-2} \times 19 \times 10^{-3} = 38 \times 10^{-5}$ that of a perfectly scattering screen. It is equal at most to the value for an optically pure air layer of

$$\frac{38 \cdot 10^{-5}}{2.25 \cdot 10^{-8}} = 16.9 \cdot 10^{3} \text{ cm},$$

or 169 m at 0° centigrade and 760 mm Hg. If the atmosphere of Mercury has a composition similar to that of our air, its thickness must not exceed 169/8000 or 21/1000 that of Earth atmosphere (1). The presence of fine particles or of water vapor would still decrease this value. On the other hand, from the point of view of Johnstone Stoney (2) gases that only scatter slightly such as helium and hydrogen could not remain in large quantities on Mercury because of their small densities and the small mass of the planet.

Clouds

The regularity of the variations of the polarization of Mercury and the perfect similarity of these variations with those of the Moon tend to prove that no significant part of the surface of Mercury is covered with clouds comparable to those of the Earth for the series of measurements made on this planet. Indeed, suppose first that there existed on the crescent of Mercury a cloud of droplets similar to those of the Earth clouds, scattering only 1/1000 of the light received by the crescent from the Sun, or approximately 1/20 of the light Mercury sends us around its greatest elongation. By referring to curve B of Fig. 46 we see that the polarization of such a cloud varies very rapidly. For an angle of vision of 90° it exceeds that of Mercury by 250/1000 and conversely for an angle of 115° it is smaller by 170/1000. By dividing these figures by 20 we obtain approximately the quantities by which the cloud would have to change the polarization of Mercury for these two angles of vision. It would increase the polarization by 12/1000 in the first case and would decrease it by 8/1000 in the second case. The presence of a very small or very transparent cloud, formed by droplets similar to those of our clouds would be enough to markedly change the shape of the polarization curve for Mercury. From the curves C and D of Fig. 47 we see that the finer water droplets would have an even greater influence. The same would hold for ice crystals such as those of curve E of Fig. 47. The droplets would decrease the polarization and the ice

(1) A still thinner atmospheric envelope could be detected by comparing the polarization of the terminator of Mercury around the center with that near the horns. During the series of observations made, the images were however generally too poor to permit this comparison.

(2) Of Atmospheres upon Planets and Satellites, Scientific transactions of the Royal Dublin Society, November 1897.

crystals would increase it. Then the similarity between the curves for the Moon and for Mercury would only be accidental, which is evidently improbable.

On the other hand, it is difficult to admit the existence on Mercury of water in the liquid state, and a fortiori in the solid state. The side turned toward the Sun (1) has undoubtedly a high temperature because it receives from the Sun, without interruption, a radiation four to seven times higher than the radiation we receive during the day. This circumstance must prevent the formation of ice crystals. Also, in order that there may be water in the liquid state on Mercury, the atmospheric pressure at ground level should exceed 4 mm. Since gravity on Mercury is 4/10 that of our own, this figure represents an atmospheric mass per unit area greater than 1/76 that of the Earth's. This quantity is close to the limit we found (French page 145). But, under these conditions Mercury's atmosphere would contain a high proportion of water vapor and we know from Fowle's measurements that when the vapor is mixed in small quantities with air it behaves as if its scattering powers were approximately 60 times greater than that of pure air (2). The atmosphere of Mercury would have to send us an amount of polarized light completely incompatible with the observations.

White patches whose intensity and position were not constant were, however, observed on Mercury on several occasions by Schiaparelli, and their existence was recently verified by Antoniadi. If these patches are clouds, one would have to suppose that these clouds are made up of dust particles detached from the surface of Mercury and relatively thick compared to the wavelength of light.

Mars

Ground

The ground of Mars is even more difficult to analyze than that of the Moon because of the clouds which fairly frequently cover it. As we saw in Chapter III, even when those veils are not visible their presence can still be detected by irregularities in the polarization curve and by noticeable differences between the planet edges and its center. From my observations of 1922 it seems that Mars was in great part without clouds between June 11, the date of opposition, and July 30. The polarizations found during that period are therefore seemingly relative to the ground proper of the planet or to the ground plus atmosphere as a whole. The part of the curve before July 30 extends to the angle of vision of 36°. It is almost identical to that of the Moon. Around the minimum it is 1.5/1000 higher than that of our satellite; then, for increasing angles of vision these two curves approach each other and become one, to within 1/1000.

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(1) The rotation of Mercury around its own axis in a time which is equal to that of its revolution around the Sun, discovered by Schiaparelli, was recently confirmed by the remarkable observations of Antoniadi.

(2) CABANNES, L'Astronomie, October 1924, p. 470.

A better agreement could be reached by comparing the ground of Mars to that of lunar "grounds" which have almost the same albedo. The observed ground was in great part a continental ground because the center of the disk occupied latitudes between +6° and +10° and it is known that the "seas" are rare in these regions. This agreement of the two curves is very remarkable and can hardly be attributed to chance. The facts appear to suggest that there exists at the surface of the continents of Mars a powder similar to that covering the continents of the Moon.

The constitution of the "seas" of Mars is more difficult to interpret. The largest ones appeared often to be pale during the observations and their polarizations hardly differed from that of the ground. Perhaps they possess a vegetation very widely distributed so that it hides the ground. On the other hand, the most intense ones are small, which makes the study of their polarization difficult. The Southern polar cap frequently showed a much stronger polarization than the Earth snows but this polarization was increased by the obliqueness of the rays scattered toward the Earth and the observations did not allow us to define the part due to this obliqueness. The irregular variations which the polarizations went through could be due to fairly frequent clouds above this cap. The persistent white spots of Nix Atlantica and Nix Olympica which are seen around the tropics have a much more favorable situation for determining their nature. I frequently observed Nix Olympica in 1926 but this spot was too small to permit measurement of its polarization.

Certain white patches appeared on the rising edge of Thyle II and on Aonius Sinus; they could be formed by transparent corpuscles such as those of white frost because when examined very obliquely they had, like Earth snow, a fairly strong polarization by refraction. Clouds would never give any polarization under these conditions.

The continents of Mars, like those of the Moon, generally do not show this phenomenon. I have observed it, however, on Arcadia at the rising edge. This region could have been covered by a deposit of white frost too light to affect the tint of the ground. The dark spots which show this polarization in the very obliquely scattered rays could be covered with vertically rising vegetation such as grass. This would be the case for example of Mare Chronium and the neighboring polar seas, but, unfortunately, the limited number of observations does not allow us to conclude decisively in favor of the assumptions in question.

Atmosphere

In order to obtain an upper boundary to the atmosphere of Mars, we shall assume, as for Mercury, that the coincidence between the curves of Mars and of the Moon are accidental and that the observed polarizations are due in part to the ground of Mars and in part to a transparent atmosphere. First, let us apply formula 8 (French page 143). For an angle of vision of 40°, when this atmosphere is fairly pure, the polarization of Mars reaches 25/1000. Its albedo during the full phase is slightly higher than that of Mercury and must be of the order of 0.2 (1). Substances of

(1) This albedo is very poorly known. Zöllner gives the value of 0.267. The measurements made by Zöllner and Seidel (Photometrische Untersuchungen, Leipzig 1865) on the brightness of

similar hues which yielded the weakest polarizations for an angle of 40° are volcanic ashes. The figures found on these substances do not go below 13/1000. The real polarization P_1 of the continents is undoubtedly not smaller than this value. The polarization P_2 of a transparent atmosphere assumed illuminated only by the Sun is equal to

$$\frac{1 - \cos^2 40^\circ}{1 + \cos^2 40^\circ} = 0.26.$$

Around the center of the disk the light of the atmosphere with respect to that of the planet is therefore at most

$$\frac{0.025 - 0.013}{0.26 - 0.013} = 0.049$$

or at most 1/20 the light scattered by the continental ground around quadrature. The brightness of this ground is then approximately 0.2 times that of a perfectly scattering screen normally illuminated. That of the atmosphere is therefore smaller than or equal to 0.05×0.2 or to 1/100 that of the screen.

As we saw before (French page 144) the brightness of a 1 cm thick layer of air normally examined and illuminated normally with respect to the visual ray is 2.25×10^{-8}. At an angle of vision of 40° it would be:

$$2.25 \cdot 10^{-8} (1 + \cos^2 40^\circ) = 4 \cdot 10^{-8}.$$

The scattering power of the atmosphere of Mars is therefore at most equal to that of a layer of pure and dry air of thickness

$$\frac{10^{-2}}{4 \cdot 10^{-8}} = 2.5 \cdot 10^5 \text{ cm or } 2500 \text{ m}$$

It is smaller than a third of the minimum value reached by our atmosphere when the latter is very pure. This number is probably still too high. Under the conditions mentioned, when there is no cloud on the disk the polarization of the edges, measured around quadrature on a width of 1 second of arc, should exceed that of the center by about 15/1000. Except in some points where the patches were visible I have seen no phenomenon of this sort. If there is an increase at the edge it is probably less than 1/5 this value. This fact limits the atmosphere of Mars to 1/15 that of the Earth (1).

Mars with respect to that of the Sun, lead to the value of 0.17. The Annuaire du Bureau des Longitudes gives 0.25. Finally, Russel calculated this albedo from the brightness of Mars measured at the quadrature and found a value of 0.139.

(1) To accept a thicker atmosphere one must suppose either that it is formed by weakly scattering gases such as hydrogen and helium, or that it contains fogs, even when the atmosphere is pure, which bring the polarization to a value close to that of the ground. These two assumptions are of course very improbable.

If the atmosphere is made up of oxygen or nitrogen, as a result of the weak gravity on this planet the ground level pressure should be smaller than 18 mm Hg. This limit is not against the existence of liquid water at the surface of Mars.

Clouds

General Fogs

As we saw (French page 53) the fogs which were observed on the planet in mid-December 1924 brought about a considerable decrease in the polarization. Changes which were similar but weaker occurred in 1922 and 1925 around the quadratures for angles of vision greater than 30°. These changes seemed also to be due to fairly light fogs so that they escaped the simple observation. For angles of vision from 30 to 45° the light scattered by these fogs had a polarization very different from that of the ground and was generally very weakly positive, or even slightly negative. None of the clouds so far studied have this kind of polarization. It would be interesting to look for it on ice crystals or on increasingly thinner grains of powder.

Local Clouds

Certain white patches which appear along the edge of Mars have, as we observed, a peculiar polarization, similar to that of white frost. Others polarize the light in a plane either parallel or normal to the plane of vision. They are visible even when Mars is completely covered with fogs. They are therefore high altitude clouds, as shown by Antoniadi. The whitest are the most strongly polarized. For angles of vision of roughly 40° the white patches have very different polarizations, sometimes strong and positive, sometimes negative, which seems to indicate that they are made up of parts having different thicknesses.

Venus

Clouds

The polarization curve obtained for Venus differs in all respects from that of the solids, whereas its numerous inversion points bring it closer to those pertaining to the clouds of droplets. This circumstance, together with the high and uniform brightness of Venus, leads us to consider the planet as being completely covered with clouds. We cannot therefore know the constitution of its ground. We shall attempt however to determine that of the cloud layer which covers the ground.

Let us examine the curves for transparent clouds which are given in the present work by Figs. 46 and 47, and the information obtained by Soret on opaque clouds (see French page 97). We see that it is impossible to explain the effects observed on Venus with droplets as thick as that of Earth clouds. When the diameter of the droplets is decreased the differences become less. The

curve D, Fig. 47, drawn for the finest droplets shows two maxima and one minimum having the same abscissas as those of the curve for Venus, also three inversion points, two of which are found exactly on the curve for this planet. The polarization of our artificial cloud, however, in spite of it being much smaller than that of thicker droplets, is still greater than that of Venus. Let us see what the polarization would become if we could increase the thickness or the cloud density until it became opaque. From the information obtained from the study of colloids (French pages 135 to 138) in the first approximation the curve would retain its shape with ordinates three to four times smaller. This curve is drawn in dotted line (Fig. 12) next to the curve for Venus by dividing its ordinates by 3.5. The similarity between these two curves is very remarkable compared to those of the other droplets which differ so much.

We can extend the analogy even further. The light scattered by the droplets increases its intensity considerably when the observer moves to a position opposite the source. Its polarization must therefore decrease less by multiple scattering at the large angles of vision than at the small angles; this would bring the curve closer to that of Venus. In addition, because the droplets scatter a large amount of negatively polarized light, the rays received at 45° from the source and going through two successive deflections should seemingly have, for the majority of them, a negative polarization, and this would decrease the principal inversion angle and would bring it closer to that of Venus.

The polarization of Venus seems therefore close to that of opaque clouds whose top layers should be made of very fine droplets, slightly larger in diameter than 2 microns (1) and with an index very close to that of water. The existence on this planet of particles so fine is confirmed by the fact that, when the angle of vision increases and exceeds approximately 160°, the brightness of the crescent increases instead of decreasing, as prescribed by Lambert's law.

The regularities of the variations of the Venus polarizations and the small differences they show between one point and the next seem to prove that the nature of the clouds which cover the planet is very closely the same in all latitudes and does not change from one year to the next. This very remarkable fact is in fair agreement with the radiometric measurements made recently at Mount Wilson by Pettit and Nicholson, according to which the temperature on Venus should be very uniform. The difference of the ratio of polarized light between the terminator or the horns and the limb are easy to explain. Indeed on the inside edge of the crescent the Sun must illuminate only the outer part of the clouds which can be different from the deeper layers. The same does not hold for the deviations of the plane of polarization which are observed in the horns. The cause of this curious effect escapes us.

Atmosphere

The constant presence of clouds on Venus makes the lower layers of its atmosphere inaccessible. On the other hand, it is difficult to evaluate the thickness of the part situated above

(1) It would be very important to verify this conclusion in a more direct way by making such a cloud in the laboratory from a colloidal solution of grains in suspension in water, the grains having an index of 1.33 with respect to the water. They could be made by a solution of white phosphor into carbon sulfide for example.

the clouds. To do this the true polarization of the Venus clouds alone without the atmosphere should be known. From the results obtained on water droplets and the weak differences between the edges and the center of the planet we can accept as possible that for dichotomy the real polarization of the clouds does not differ by more than 10/1000 from the one which was observed around the center of the planet. With formula 8 (French page 143) we should take $P - P_1$ equal at the most to 0.01. $P_2 - P_1$ is close to 1. Taking for the average brightness of Venus 1/3 that of a normally illuminated white screen we find that the scattering power of the atmosphere of Venus must at most be equal to that of a layer of pure air of

$$300 \cdot 2.25 \cdot \frac{1}{10^{-8}} = 1.48 \cdot 10^5 \text{ cm}$$

or approximately 1,500 m thick.

The barometric pressure should be less than 1/5 that of the surface of the Earth. It could still be sufficient to permit the formation of water clouds. This evaluation, which has no precise basis, must be considered only as a simple assumption.

Jupiter

Clouds

Since the known portion of the polarization curve of Jupiter is very short it is difficult to ascertain the nature of the cloud belts which surround the planet. Note however that this curve represents very weak polarizations and very different from those of the clouds studied. New experiments would therefore be necessary. They should be made essentially on fogs of ice crystals whose diameter should be made to vary. We saw (French page 76) that the polarization of the two equatorial edges of Jupiter differ systematically from each other and that the polarization is always algebraically higher at the east rim than at the west rim. This effect seems to be due only to an influence of the solar radiation on the higher cloud layer of Jupiter. The altitude and the transparency of this layer should change during the day.

Atmosphere

The increased polarization observed on the equatorial rims of Jupiter seems first to indicate the presence of a thick atmosphere above the clouds. In order to produce such an effect, in spite of the small angles of vision, the atmosphere under consideration should have a very high scattering power, similar to that of the Earth's atmosphere under good weather conditions. The light coming from the rims of Jupiter would thus be strongly polarized along a plane parallel to these rims, by a mechanism similar to the one which gives rise to the zero points and to the horizontal polarization which is observed on our globe along the opposite direction to the Sun.

In the equatorial regions of Jupiter this is not so, because the plane of polarization of the east and west rims is always almost perpendicular to these rims and their ratio of polarized

light goes to zero at opposition. The cloud belts are therefore not surrounded by a thick atmosphere. The observed increase of polarization must be due to other causes, e.g., to the decrease in transparency of the cloud layers when observed very obliquely.

The curious polarizations of the polar caps should on the contrary agree very well with the presence of a thick or highly scattering atmosphere underneath the clouds. The often bluish light from the caps should come in great part from this atmosphere and its polarization along the plane parallel to the edge should be produced by the above mentioned mechanism. The atmosphere would be veiled progressively towards the equator and this would induce the observed decrease of polarization. Under this assumption the polarization of the caps should increase around quadrature because the polarization of the directly scattered rays is added to it. The increase, produced for the angle of vision of 11°40', should be 21/1000 if the light from the whole caps came from the direct Sun rays as scattered only by the atmosphere. Actually this is not the case because of the multiple scattering and the fogs which progressively veil the caps towards the equator. Around the pole the influence of the angle of vision is mostly felt. It is very improbable that it will reach half the calculated number or 10/1000. Under these conditions it seems difficult to notice this influence because of the irregular variations undergone by the polar caps. The whole series of observations, although favorable to our assumptions, do not provide any confirmation.

Saturn

Clouds

It is even more difficult to know the nature of the cloud belts of Saturn than it is the belts of Jupiter because the former are generally very pale and seem strongly veiled. Note, however, that the whitish zone which appeared in the North hemisphere between June 9 and 7 July 1924 showed a polarization similar to that of the clouds of Jupiter.

Atmosphere

The very small portion of available curve for the polarization of Saturn is almost that of a transparent gas observed on a dark background. It is difficult however, to attribute the measured polarizations to the atmosphere of Saturn. This atmosphere should in fact scatter a lot of light to explain the high albedo of the planet. In this case the multiple scattering would produce a constant and strong polarization near the edges and parallel to these edges. This effect exists only around the poles, whose puzzling phenomena should be explained in the same manner as for Jupiter. The very significant changes of the polarization which are observed on the South cap seem to be produced by fogs having a variable opaqueness.

Rings of Saturn

Inner Ring (B)

As we mentioned before the plane of polarization of the bright ring which is within the Cassini division is always perpendicular to the plane of vision. Its polarization is consequently due to the simple scattering of the light which it receives directly from the Sun, and the curve of polarization (Fig. 22) is very different from those of the Moon and Mars. The inversion angle is much smaller (about 8° instead of 24°0) and the negative minimum is reached for 0°50' instead of about 10°.

I studied only a small number of solid substances at these low angles. The measurements made at 2° allow us to see that the curve for the inner ring is similar to that of many non-powdered minerals; specifically to those which were obtained for the broken faces of lavas and granite samples. This curve differs however much more from those of the powdered lavas and ashes. From this it seems that the inner bright ring of Saturn is not made of very fine powders, but of more or less thick blocks. The study of very clear minerals at very low angles of vision should give more precise data on the nature of the rocks which constitute the ring.

Outer Ring (A)

The effects observed on the outer ring seem very complicated. It is indeed very difficult to explain the differences that exist between the two arches. I have tried however to determine if it is possible to account for their polarizations by assuming them to be due to two simultaneous causes. These are:

1. The simple scattering of rays received directly from the Sun by the two arches.

2. The scattering of rays received by the arches from the illuminated hemisphere of Saturn or the scattering or multiple reflections which could be produced between the blocks which are likely to constitute the ring.

The first cause should give rise to an identical polarization on the two arches, either in a plane going through the Sun or in a perpendicular plane (the latter case being the most probable). The second cause could give rise on the two arches to two different polarizations, but, due to reasons of symmetry, the ratios of polarized light would necessarily be the same and the planes of polarization would be symmetrical with respect to the axis of Saturn and its rings.

Let us try to check this assumption by taking the polarizations found on each of the two arches of the outer ring as resulting from the mixture of:

1. A light component A having on each arch the same intensity, the same ratio of polarized light and the same plane of polarization, perpendicular to the plane going through the Sun.

2. A light component Bp for the preceding arch, B_S for the following arch, both having the same intensity and the same ratio of polarized light but different planes of polarization.

With these conventions we can obtain by a simple construction (1) the quantities of polarized lights Q_A and Q_B which the light components A and B must contain with respect to the total light, and the planes of polarization Bp and B_S. The values obtained for these quantities appear in Table 16. The curve 52 respresents the changes of the quantities Q_A and Q_B as a function of the angle of vision. Since the light coming from Saturn is negligible compared to the direct Sun rays the quantity Q_A represents approximately what should, according to our assumption, be the polarization of the outer ring due to simple scattering of the Sun rays. The corresponding curve is similar to that of the inner ring and to that of many solid substances. The quantity Q_B should remain constant in our assumption. It seems to have decreased slowly from 4/ to 2/1000 when the angle of vision increased.

On the other hand, the Table shows that the planes of polarization Bp and B_S are far from being symmetrical with respect to the axis of Saturn. The position angle of their bisector varies from 24° to 55°, whereas that of Saturn's axis remained between 3° and 5°.

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(1) The resulting polarization can be obtained by adding vectors whose lengths are proportional to the elemental quantities of polarized light and which make with a fixed origin vector angles which have twice the value of the position angles of their planes of polarization; assuming all these quantities known. The length of the resultant vector represents the total quantity of polarized light and the angle it makes with the origin vector is equal to twice the position angle of the plane of polarization.

This property can be proved in the following way. Suppose there are n partially polarized light components $i, i_2, i_3, \ldots, i_n$ with ratios $p_1, p_2, \ldots p_n$ and with position angles for the plane of polarization $a_1, a_2, \ldots a_n$. Let β be the position angle of the principal plane of the polarimeter. Following the proof of Chapter I, (French page 15), every component acts on the polarimeter as if it were polarized along its principal plane, with ratios

$$p_1 \cos(2\alpha_1 - 2\beta) \qquad p_2 \cos(2\alpha_2 - 2\beta)\ldots$$

they should consequently contain the quantities of polarized light

$$p_1 i_1 \cos(2\alpha_1 - 2\beta) \qquad p_2 i_2 \cos(2\alpha_2 - 2\beta).$$

The resultant light of intensity $i_1 + i_2 + \ldots + i_n$ acts on the polarimeter as if it had a quantity of polarized light.

$$p_1 i_1 \cos(2\alpha_1 - 2\beta) + p_2 i_2 \cos(2\alpha_2 - 2\beta) + \ldots$$

having for value the projection on the polarimeter principal plane of the resultant of the vectors having lengths $p_1 i_1 \ldots$ and angles $2_1 \ldots$. Let P I be the length of this resultant and $2a_0$ its position angle. Since this holds for any β, the total light behaves as if it contained a quantity of polarized light PI, with the position angle of its polarization being a_0.

TABLE 16
Component Polarizations of the Outer Ring

Date			V	X	Q_A	Q_B	B_P	B_S	∝
1925	5	May	0°31'E	141°	4.5	3.7	19°	109	2°
	3	June	3 19	112	6.1	3.2	19	45	1
	15		4 16	111	6	2.1	10	59	1
1926	19	June	3 30	109	7.1	1.4	3	93	3
1927	14	May	1 14	90	5.6	3.8	8	110	4
	24		0 16	50	2.7	4.5	39	90	4
	26		0 12	0	1.3	3.6	11	96	4

V: Angle of vision.
X: Position angle of the plane of vision.
Q_A: Ratio of polarized light due to direct sun rays.
Q_B: Ratio of polarized light due to an unknown cause.
B_P and B_S: Position angle of the hypothetical polarization for the preceding and following arches.
∝: Position angle of Saturn's axis.

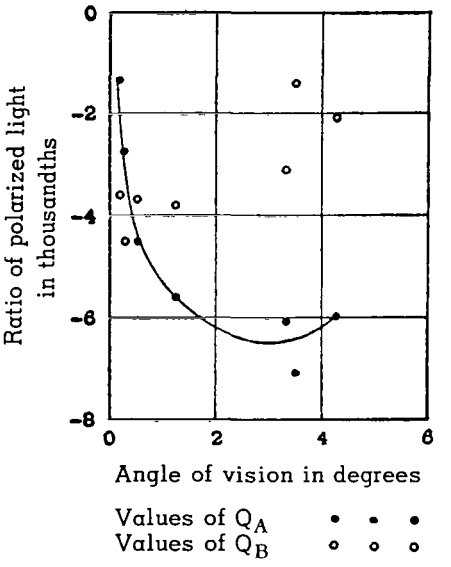

Figure 52. Outer Ring of Saturn Component Polarizations

In spite of the calculated curve being a plausible one for the ratio of polarized light which the direct Sun rays should produce, our assumption does not give a full account of the observed effect.

Our assumption leads to the following consequences. If the polarization of the outer ring is measured by orienting the polarimeter so that its principal plane is either parallel or normal to the axis of Saturn, the same values must be found on the two arches. I performed this experiment on several occasions and I found different values, often of opposite signs. They did not change when the polarimeter was turned by 180°. This obvious lack of symmetry is very surprising, since the rotation of the ring carries continuously, from one arch to the other, the same matter (1) which forms it. The outer ring of Saturn appears therefore to be the source of still very mysterious phenomena. More numerous and more accurate measurements are required to determine their causes with certainty. In particular, it would be interesting to find whether the polarization of the outer ring becomes zero exactly during oppositions, when the angle of vision becomes less than half the apparent diameter of the Sun as seen from Saturn. This condition is met once every fifteen years for a duration of six hours at most, and will occur again in July 1931.

(1) It is possible however that the visible parts of the two arches of the outer ring do not show the same area. Assume for example that the ring is composed of particles rotating about themselves in such a way as to always present the same face toward the planet, as in the case of most satellites. The front of these particles could have undergone changes due to collisions with meteorites which would make the back different from the front. It seems difficult to otherwise explain the configuration presented sometimes by the two arches of the outer ring.

CONCLUSION

Now that we have described the research, the results obtained, and the consequences drawn from these results, let us review the research, and try to see as a whole the knowledge which was acquired in the course of this study. Contrary to the most popular and recent opinion, the light from the first five planets have measurable polarizations which can be found most of the time with a simple Savart polariscope, at least on certain points.

Around the center of the planets the light is polarized by simple scattering, always in a plane either parallel or perpendicular to the plane going through the Sun. The ratio of polarized light depends essentially on the angle of the incident Sun rays with the direction of observation. It is zero exactly at opposition. The relationship which connects these two quantities characterizes the nature of the ground, the clouds, or the atmosphere of each planet, and often permits the determination of their constitution by comparison with Earth substances. Sometimes this relationship is quite regular and remains constant from one year to the next, which indicates that the physical state of the planets did not change. Sometimes, however, the polarization is momentarily modified, which generally reveals the presence of an extended perturbation of its atmosphere. In some cases, when the planet and the Earth resume the same relative positions, the ratio of polarized light goes through somewhat different values which generally reveal progressive modifications in its atmosphere.

The ratio of polarized light varies from point to point on the planet. Near the edges, certain regions have a polarization in a plane at an oblique angle with respect to the direction of the Sun, which does not seem to go to zero at exact opposition. This effect can be attributed in part to a refraction of the rays scattered by the ground, or sometimes to multiple scattering inside the atmosphere. On certain points the polarization undergoes deviations whose causes are still unknown.

New Results

The research described in this work presents a certain number of new contributions, the most important of which are:

1. The accurate knowledge of curves belonging to each planet, where the general polarization of light of the planet is plotted as a function of the angle between the incident Sun rays and the direction of observation.

2. The existence on the Moon and on Mars of a polarization perpendicular to the plane going through the Sun around opposition, becoming zero for an angle close to 24°, and then becoming parallel.

3. The property, common to most absorbing solid substances, of scattering back, along a direction close to the source of illumination, a light which is polarized perpendicular to the plane going through the incident rays. As the observer withdraws from the source the polarization goes through a maximum, becomes zero, and reappears along a perpendicular plane.

4. The remarkable similarity between the Moon and the planets Mars and Mercury.

5. The reproduction in the laboratory of a substance giving the same polarizations as the Moon, Mars and Mercury, i.e., a mixture of volcanic ashes.

6. The considerable influence of fogs on the polarization of Mars, which sometimes escapes the simple observation.

7. The very weak scattering power of the atmosphere of Mars, and more specifically, that of Mercury.

8. Accurate data on the polarization of clouds of water droplets of various diameters indicating that a thick cloud of very fine droplets gives polarizations very close to those of Venus.

9. The deviations of the plane of polarization on the horns of Venus are equal and of opposite sign.

10. The effect of the solar heat on the atmospheric condition of Jupiter, which manifests itself by a difference between the two rims having always the same sign.

11. The discovery on the polar caps of Jupiter and Saturn of a peculiar polarization, almost independent of the positions of these planets with respect to the Sun, and presumably of atmospheric origin.

12. The same phenomenon is constant on Jupiter and highly variable on Saturn.

13. The difference in constitution between the two bright rings of Saturn which are separated by the Cassini division. The inner ring shows properties similar to those of the best known Earth rocks, the outer ring is the source of still unexplained phenomena.

Translated for the National Aeronautics and Space Administration by John F. Holman & Co. Inc.

Translators

A. Pinto, MS
L. Pinto

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